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AGARD Flight Test Techniques Series
Volume 13
on
Reliability and Maintainability

(Fiabilité et maintenabilité)

This AGARDograph, originally sponsored by the Flight Mechanics Panel on AGARD, has been published on behalf of the Flight Vehicle Integration Panel.

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We apologize for this inconvenience.

Yours sincerely,

K Edwards .

Kelly Edwards
A/Project Manager
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AGARD-AG-300 Vol. 13

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7 RUE ANCELLE, 92200 NEUILLY-SUR-SEINE, FRANCE

AGARDograph 300
Flight Test Techniques Series — Volume 13

Reliability and Maintainability

(Fiabilité et maintenabilité)

by

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Preface

At the request of the Advisory Group for Aerospace Research and Development (AGARD) Flight Mechanics Panel, the author attempted to prepare a document outlining the rudiments of reliability and maintainability (R&M) evaluations conducted during initial flight test programs. Many military organizations prefer to defer R&M evaluations until the new equipment has been delivered to the eventual user. Other organizations do not structure R&M engineering as an integral part of the flight test team. The U.S. Air Force Flight Test Center at Edwards AFB, California has long conducted R&M evaluations during initial flight test and this document is written from that perspective.

The AGARDograph presumes an entry level R&M engineering skill and does not dwell on R&M fundamentals.

It is hoped that this AGARDograph will satisfy any need for understanding of R&M evaluations conducted during initial flight test.

Préface

À la demande du Panel AGARD de la Mécanique du vol, l'auteur a rédigé un document qui présente les principes de base des évaluations de fiabilité et de maintenabilité (R&M) effectuées lors des programmes des premiers essais en vol. Bon nombre d'organisations militaires choisissent de différer les évaluations R&M jusqu'à ce que le matériel neuf ait été réceptionné par l'utilisateur. D'autres organisations préfèrent ne pas intégrer l'ingénierie R&M dans les fonctions de l'équipe d'essais en vol. Depuis très longtemps, le centre d'essais en vol de l'US Air Force à Edwards, en Californie, réalise des évaluations R&M lors des premiers essais en vol et ce document est rédigé dans cette optique.

La lecture de cette AGARDographie exige, toutefois, un certain niveau de connaissances en ingénierie R&M.

Ce document doit permettre une meilleure compréhension des évaluations R&M effectuées lors des premiers essais en vol.

Acknowledgement
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RELIABILITY AND MAINTAINABILITY FLIGHT TEST TECHNIQUES

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SUMMARY

Reliability and maintainability (R&M) evaluations can be conducted during the initial flight test of new and modified aerospace systems. Newly developed equipment usually has only a fraction of the reliability needed. These evaluations, combined with extensive laboratory test efforts, are required to bring the system to an acceptable level of R&M performance. No flight time is normally dedicated to these R&M evaluations, but some ground time is required. Other unique required resources include trained R&M engineering personnel, R&M data, and data reduction capability. Results include identification of R&M deficiencies and measurement of R&M parameters.

1.0 INTRODUCTION

1.1 Purpose of Volume

This AGARDograph provides information to the reader who must evaluate reliability and maintainability (R&M) of aeronautical weapons systems during initial flight test. Flight test R&M evaluations are essential because R&M characteristics cannot be predicted with any degree of success. Initial reliability for newly designed equipment is normally 10 to 20 percent of the predicted value. The actual reliability begins to approach the original prediction only after considerable laboratory and flight test.

Table 1 lists the predicted reliability, laboratory test reliability, and the fleet use reliability for several different types of U.S. aeronautical equipment. The large differences between predictions, laboratory test, and actual use vividly show the need for indepth flight test R&M evaluations. This volume concentrates on flight test because of the demonstrated need to evaluate systems during actual usage. Laboratory testing is discussed only as it relates to flight test.

Table 1
Specified, Predicted, Demonstrated, and Actual Reliability
Meantime Between Failures in Hours
(Data from a 1987 Rome Air Development Center, U.S. Air Force Study)

EQUIPMENT	CONTRACT SPECIFIED	CONTRACTOR PREDICTED	LABORATORY TEST	ACTUAL USE
ALQ-131 (F-4G radar warning	17	59	47	268
ALQ-135 (F-15C radar warning)	131	169	231	66
APG-66 (F-16 attack radar)	80	150	55	97
APQ-114 (FB-111 attack radar)	137	185	212	22
ARC-164 (F-111 UHF radio)	1,000	1,626	374	168
ARC-164 (B-52H UHF radio)	1,000	1,626	374	843

R&M evaluations consist of two general areas: R&M engineering and R&M accounting. R&M engineering is the engineering practice needed to yield a reliable and maintainable product. This is the science (or perhaps art) of designing and manufacturing equipment suitable for the intended operational and support environments. During flight test R&M engineering is the process of finding and fixing problems. R&M accounting, in contrast, measures how well a particular equipment suits a specific operational and support environment. This volume addresses both the engineering and accounting aspects of R&M evaluations.

1.2 Scope

This volume will address the "how to" of conducting flight test R&M evaluations of aeronautical systems. These techniques have been used to test aircraft, missiles, and munitions. While these methods are somewhat general in nature the reader must modify these concepts for use in nonairborne environments. For example, this volume uses flight hours as a measure of operational use. A ground-based cargo transportation system might use tonne-kilometers as a measure of operational usage. Any such needed re-interpretations are left to the concerned reader.

This volume also presumes that a reader has knowledge of the fundamental tenets of reliability and maintainability. Many excellent textbooks, for the novice and for the sophisticate, are readily available.

This volume addresses system level evaluations. That is, evaluations are not limited to the air vehicle but include aspects of the system such as ground support equipment, facilities, and trainers. Further, test articles such as airborne avionics and subsystem test beds provide much useful information. Many ground test facilities such as anechoic chambers and avionic integration laboratories are co-located with and used during flight test. The R&M data from these facilities should be used in conjunction with data from flight test.

Most of this volume discusses evaluations suitable for systems with a possibility of production in significant quantity. Those systems or air vehicles built purely for research purposes (such as the American X-29) require different treatment because vehicle availability and cost of ownership are secondary considerations for such limited life efforts.

1.3 Organization

The first major section of this volume discusses the objectives of an R&M evaluation in some detail. This level of knowledge is needed to advocate, plan, and conduct R&M evaluations. The remainder of the volume proceeds in same order as a development program would. First, the development and acquisition process and the R&M flight test engineer's role is discussed. When the evaluation objectives and acquisition process are understood, the groundwork is laid for a discussion of the planning and preparation needed for a successful evaluation.

Next, test conduct, data analysis, and results reporting are discussed. At this point, the flight test effort is complete. But, the test community must monitor the fleet usage of the aircraft to learn of any test oversights and a chapter of the volume addresses that process.

Finally, the volume presents some future R&M considerations. This section, perhaps optimistically, lists some evolving R&M engineering tools and technologies that will lead to improvement in aerospace systems.

1.4 Acknowledgments

The use of specific references has been deliberately minimized. This was done to make the volume applicable to a variety of aeronautical systems. This approach also lowers the possibility of inadvertently including any proprietary or sensitive information.

Much of any value arising from this document originated with those long-departed individuals who taught and mentored the author throughout a career. The remaining value was added by individuals from the North Atlantic Treaty Organization (NATO) nations who generously contributed time and energy to consult with the author and review the document. Weaknesses and errors belong to the author.

2.0 R&M TEST OBJECTIVES

2.1 Introduction

"When you don't know where you are going, any road will get you there." Before starting any endeavor, first understand the objectives and benefits. The remainder of this chapter will discuss the objectives of an R&M

evaluation. Potential benefits, along with some examples, will also be shown.

2.2 Reliability Maturation

The most important objective of any R&M evaluation is to increase system reliability, lower life cycle cost, and increase mission capability. Initial versions of new hardware usually have 10 to 20 percent of the sought after reliability; the ground and flight reliability test effort is really a reliability maturation program. A common misconception is that R&M evaluations are only to measure R&M values. Measurement for measurement's sake can be a sterile exercise; the real value is in getting the information needed to improve the product. This point cannot be over emphasized. Declining defense budgets dictates military utility must be maximized by weapons systems that work. In the world environment today, quality is viewed as the most important characteristic of any product. The nation, the manufacturer, and the ultimate consumer that do not understand this are destined for extinction.

The classical reliability improvement effort is often called "test-analyze-fix." In a perfect world, equipment would work correctly when first delivered to the customer. That is not now, nor soon likely to be, the case. To engineer is a human endeavor and therefore, prone to errors. Such errors become noticeably more frequent on the forefront of technology. And military systems are always required to counter the most current threat. That dictates the continual use of leading edge technology. So, eliminating initial reliability problems will always be a challenge in military systems.

The reliability improvement process is commonly called "reliability growth." Like in nature, this growth does not occur unless conditions are right. Maximum growth occurs when the object is constantly fertilized with money to find and fix problems.

The process is simply to identify the root cause of failures that occur during flight test and eliminate the cause. Experience shows that the vast majority of failures do not require a design change to eliminate the failure cause. Instead, changing the manufacturing process to remove latent defects corrects over 80 percent of the problems. Changes to the manufacturing process are usually inexpensive and do not take long to implement. A common example from the early microelectronics era was electrostatic damage. One memorable case required hundreds of engineering man-hours to find the exact failure cause. The problem was eventually traced to the work of one technician whose job was to insert microelectronics packages into circuit boards. The workshop was properly designed to prevent electrostatic damage. However, when observed, the technician was not using all of the protective equipment. When asked why the employee had not worn the wrist earthing strap, the (ir)responsible assembler said that the strap was uncomfortable. A brief discussion about potential employment discontinuities caused the reliability of the employee's particular work to increase dramatically.

Other changes that do not require a re-design include changes of parts suppliers and increasing parts quality. These changes are more expensive and require more time. The most expensive efforts are those where the actual equipment design must be changed. A common cause of re-design are initial designs that are not suited to the operating environment. One U.S. attack aircraft cockpit display failed during every gunfire mission, hardly a desirable feature in an air-to-ground weapons system.

Figure 1 shows the percentage of environmentally caused failures by specific environmental factor. Temperature or vibration cause most environmental problems and may require instrumenting the aircraft to define the problem. The instrumentation installation, data acquisition and analysis, and eventual re-design are long and costly processes. One recent U.S. avionic development program was blessed with both thermal and vibration problems sufficient to cause an 18-month program delay.

2.3 Maintainability Maturation

The idea of "maintainability growth" is not as accepted or as well studied as reliability growth, but maintainability will improve if enough resources are correctly applied to that objective. While the improvement will not be an order of magnitude (as sometimes happens in reliability), the resultant cost savings and increase in capability will be worthwhile. The two segments of a repair task most amiable to improvement are fault isolation and fault correction. Improved trouble-shooting procedures, test equipment, and built-in-test capability will all decrease task time. Special training will improve performance of very difficult tasks.

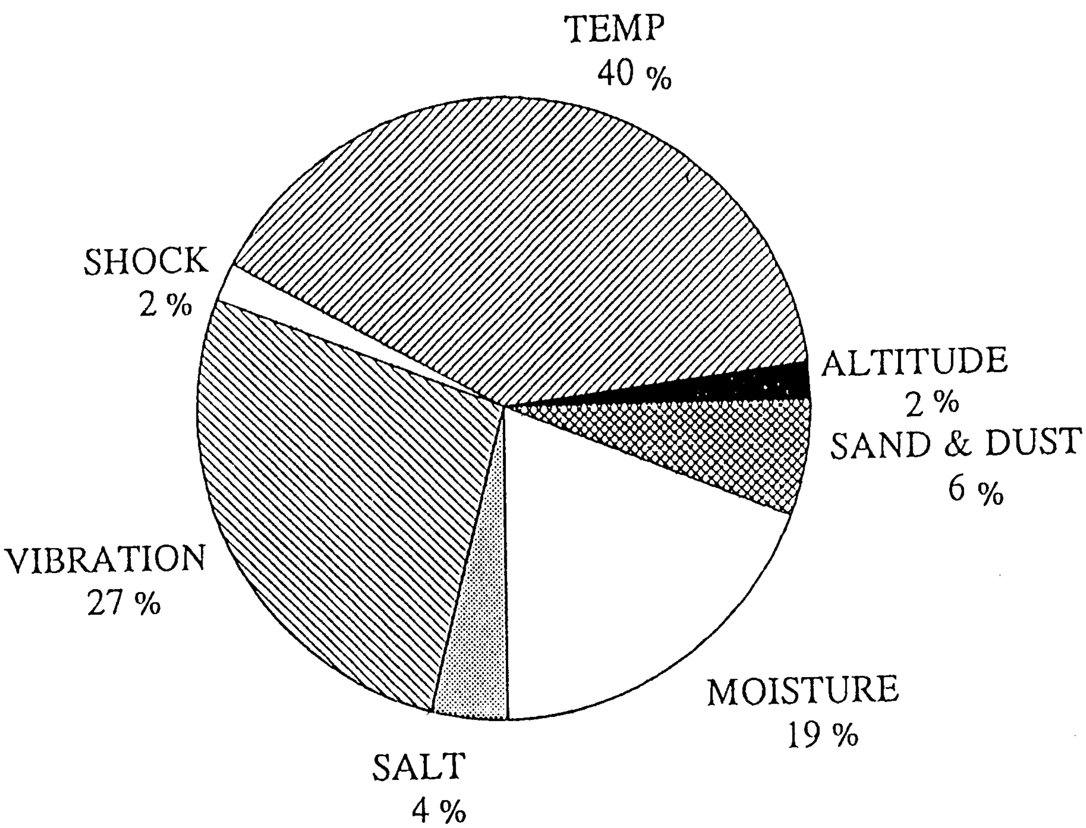

Figure 1 Environmental Effects on Reliability

A rapidly developing technology for fault isolation is the use of the so-called "expert system" from the field of artificial intelligence. These systems query the user about the failure symptoms, apply these symptoms to an internal set of rules, and derive a diagnosis. Development of these rules is a natural flight test objective.

The fault correction segment of repair time is largely fixed by the physical design of equipment, but changes to procedures, special tools, and training can decrease the actual repair time. Sometimes the task may be difficult enough to warrant design changes. A case in point was an air superiority fighter with a high-visibility canopy that was very hard to install and adjust. The manufacturer initiated and paid for an extensive re-design in the interest of improving producibility. In another instance, the first attempt to change an engine in a flight test aircraft required six clock hours to complete. After some minor engine trailer changes, improved tools and training, the change required 45 minutes.

A unique flight test maintainability objective is development and demonstration of integrated combat turn (ICT) or "quick-turn" procedures. An ICT is the recovery after landing, rearming/refueling and re-launch of a combat aircraft. Careful optimization of personnel, procedures, and equipment placement is necessary to minimize time and maintain safety standards.

An often overlooked maintainability objective is development or refinement of the maintenance plan. The maintenance plan defines, among other things, whether a specific part is repairable or discarded upon failure. For repairable parts the maintenance plan states if a part is repaired on the vehicle, sent to a local specialized shop, or returned to a remote repair depot. Initial maintenance plans are based on predicted failure frequencies and estimated repair times. When actual R&M data becomes available, the plans invariably require considerable revision. With 8,000 major replaceable units, the B-1B aircraft is an excellent example of the possible complexity of the maintenance planning task.

2.4 Duty Cycle Improvement

A high pay-back evaluation objective is to assure that all equipment has the lowest possible duty cycle. That is, to make certain that vehicle subsystems are operated or stressed only when needed. While this is a seemingly obvious objective, experience shows that almost all aircraft have some equipments that operate more than required. The fighter aircraft UHF radio that operated any time that ground power was applied to the aircraft was a good example. The only way to prevent operation was to open circuit breakers that were not accessible from the cockpit. The aircraft was modified to prevent unneeded ground operation and the radio reliability (measured in flight hours) increased threefold.

A unique example occurred on a test aircraft that had a very high failure rate of fuel quantity probes. The problem was most puzzling because similar aircraft did not have the problem. Investigation showed that the aircraft was instrumented with a system that required lengthy ground operating periods to calibrate. The fuel quantity system was also energized whenever ground power was applied. The test base had a high bacteria count in the jet fuel supply. The continuous voltage applied to the capacitive type fuel probes caused the bacteria to "electroplate" between the probe plates and short out the quantity sensor. Changed operating procedures opened the fuel quantity system circuit breakers whenever possible and vanquished the problem.

Table 2 shows the subsystem operating time-to-flight time ratios for an attack aircraft. Some equipment, such as the automatic direction finder, is not used every flight and has an appropriately low ratio. In contrast, the electrical power system is used during aircraft maintenance and has a higher ratio. These ratios are obtained by using the clocks (also called elapsed time indicators [ETIs]) on individual units and the aircraft flight time. When test aircraft do not have time indicators installed on the individual units it is necessary to add clocks. With these ratios, it is straightforward to identify the high usage items and see if beneficial changes are possible.

Some currently used equipment clocks are unreliable mechanical chronographs that are seldom used after testing is complete. The use of microelectronics "history chips" promises increased reliability and greater utility. These memory units could record usage, on/off cycles, and other measures of cumulative stress such as thermal cycles. Other information such as a failure history may prove of value.

Table 2
Selected Equipment Operating Versus Flight Time Ratio For the A-7D Fighter Aircraft (AFFTC-TR-70-27 A-7D Category II R&M Evaluation)

EQUIPMENT	OPERATING HOUR/ FLIGHT HOUR
Flight Controls	1.3
Propulsion	1.3
Air Conditioning	1.3
Electrical Power	2.7
Lighting	2.7
Hydraulics	1.4
Automatic Direction Finder	0.4
Forward Looking Radar	1.3
Air Data Systems	2.0

2.5 Contractor Performance Verification

The R&M performance requirements should be included in every aircraft contract just as other requirements such as payload, range and weight are. The contract should also clearly state how achievement of R&M requirements is to be verified. Because R&M performance improves during the development phase it is not possible to demonstrate fully mature R&M characteristics during test. But it is possible to demonstrate that satisfactory progress is being made towards achieving mature R&M values. Aircraft contracts should state what levels of R&M performance will be achieved by completion of test. Then, before a commitment to high-volume production is made, needed fixes and the associated risks should be assessed to insure a high probability that production systems will have the required R&M characteristics.

Many current aircraft contracts include financial incentives to help insure satisfactory (or better) R&M performance. These incentives take the form of monetary awards (as much as U.S. $50,000,000) given in increments at major program milestones. When a large increment is to be decided by flight test results, the measurement of contractor performance becomes a very visible flight test objective.

Similarly, when the contractor must prove minimum R&M performance levels during test or correct deficiencies at his expense, the performance measurement objective becomes very visible.

2.6 Deficiency Identification

A major result of an R&M valuation is the identification of problem areas where corrective action must be taken before the system is produced in quantity. Whether the problem is reliability or maintainability centered, the process is similar. Once a problem is suspected to exist, enough evidence must be gathered to prove or disprove the problem. The evidence may be instrumentation data, film or video footage, or subjective information such as pilot descriptions. In many ways the R&M test engineer must build a case for the deficiency just as a lawyer prepares a case. The evidence must be clear and convincing and the seriousness of the problem must be apparent. Further, enough data must be available to allow the manufacturer to correct the problem.

2.7 Improvements

During flight test programs there are often opportunities for substantial system improvement even if the aircraft is not deficient in any respect. If the system works as designed and as agreed-to between the contractor and customer, no deficiency exists but the system may not be optimal. This may occur when a major technology advance becomes available after system design but before the beginning of full-scale production. Sometimes contractors are reluctant to use new techniques or technologies if they were not the originators (the not-invented-here attitude). An obvious function of flight test is to identify such potential improvements. Again the evidence must be clear and convincing and the potential benefit must be apparent. Aircraft radial tires offer an excellent example of such improvements. While the European aerospace community was beginning to incorporate these improved-life tires, some of the American manufacturing community was lagging behind. Because of flight test involvement, American fighters are beginning to be equipped with radial tires. The relatively new maintenance-free, sealed lead-acid battery is another example. When a fighter

development program encountered problems with a more conventional nickel-cadmium battery, the flight test reliability engineers convinced the manufacturer to adopt the new battery and improve reliability while significantly lowering life cycle cost.

2.8 Mature System Capability

Prediction or estimation of the R&M driven capabilities of the weapons system is a very valuable result of the flight test program. Specifically, maximum sortie rate and aircraft turn-around time (time between sorties) are of interest. The problem of predicting mature system maximum sortie rate in an operational environment from flight test data are nontrivial. A simulation model of some complexity must be used to translate flight test measures such as repair/service times and frequencies into operationally oriented measures such as sortie rate under an operational environment.

In contrast, turnaround time is a fairly straightforward development and measurement process. The process begins with development of a complete list of the tasks to be done during turnaround. An implicit assumption is that the aircraft does not require repair and requires only servicing before the next flight. When the task list is complete, including personnel required and equipment needed, the task sequence must be optimized for minimum overall time. Safety must be considered during the task-ordering process. For example, refueling the aircraft while simultaneously running an ammunition loader may not be the safest way to order the tasks. Models or scale drawings are helpful in determining optimal support equipment placement. Once a planned sequence is developed, it (and perhaps several alternate methods) should be tested for suitability and the overall time recorded. Normally such tests result in refinement to planned procedures and lower times.

2.9 Logistics Requirements

Many mature system logistics requirements can be readily predicted from flight test data. While flight tests are normally not long enough to measure the reliability (and the resulting spares requirements) of all components of the aircraft, those parts with low reliability can be measured to a reasonable confidence. The parts with the lowest reliability are usually the high cost items (such as airborne radar) so a large part of the spares budget can be allocated from flight test data. The useful life of parts characterized by wear-out, such as tires and brakes can be accurately measured and spares requirements forecast.

Maintenance personnel requirements are not so easily determined because of the large differences between the test environment and the actual intended use environment. Once the repair/service frequencies and times are measured in flight test, the logistics models discussed earlier are used to extrapolate from the test environment to the end use environment.

Test equipment utilization rates are another important logistics consideration that requires a translation to be meaningful in the operational environment. The flight test task is to measure the "shop visit" frequency and the test equipment usage time for the different parts. Next, a maximum acceptable work backlog must be decided. Because the times that failures occur are random, the work backlog will also be random. The number of spares available must be considered when determining the acceptable work backlog for a given unit. When the backlog exceeds the spares available, an aircraft will be grounded until a unit is repaired. When "visit rate," test equipment use times, and acceptable backlog are known it is an exercise in queuing theory to estimate the number of test equipment hours needed to support a given number of aircraft at a given utilization rate.

Program unique facilities (sound suppressors, fuel cell repair barns, etc.,) are treated very similarly to test equipment. Once the "visit" frequency is measured and the maximum tolerable facility backlog is determined then the number or capacity of facilities is a queuing theory problem.

2.10 Summary

The objectives listed include: improving and measuring R&M performance, identifying deficiencies, lowering usage, and estimating logistics support requirements. Benefits include increased in-commission rates, lower support costs, and more accurate logistics planning factors.

3.0 DEVELOPMENT/ACQUISITION PROCESS

3.1 Requirements Definition

The requirements' definition process lays the foundation for the development of any system. The

importance of well defined and justified requirements cannot be over emphasized. Several studies show that approximately 75 percent of the system cost is fixed by the finalized requirement. While the requirements may change during the process the cost will not decrease. Generally, changes during the system development invariably increase costs as the system grows more complex to adopt to emerging threats or other changes in the anticipated mission.

The test agencies must be involved in the requirements definition process for several reasons. First, the experienced tester has a large repertoire of "lessons learned." These are both negative ("we'll never try that again") and positive ("that worked so good let's try it again next time"). This knowledge base can be invaluable to the requirements formulation process.

The experienced tester can often add an important element of realism to the process. When the requirements definition is left to the eventual system user the inevitable result is over specification or asking for capabilities of marginal utility ("goldplating"). An excellent example was provided by a trainer aircraft that originally required an inertial navigation system. A simple calculation showed that the life cycle cost for the inertial navigation system would be billions of dollars in total cost (approximately 20 percent of the total cost of ownership).

3.2 Contractual Requirements

Once relatively firm requirements are set, the next step is to translate requirements into contractual format such as a system specification (which states requirements) and a statement of work (which defines required processes). The test agency must participate in preparing the system specification to ensure that stated requirements can be measured during test. A requirement without a corresponding compliance assessment is merely a goal. Further, because R&M measures are very sensitive to the large differences between the test and field use scenario, R&M contractual requirements must be carefully written. These requirements must reflect the needs of the user, but must be measurable while the immature system is being tested in an often beneficial environment. There are a number of significant differences between the test and field use scenario. These differences include; differences in maintainer skill levels, immature technical data, and others. Some of these factors bias R&M results pessimistically while others make the system appear better than it actually is. Again, the experienced tester is often needed to help state requirements that realistically satisfy the users, but can still be measured during the test program.

The statement of work defines processes to be followed and specific results to be produced during the contractor's development program. Ideally, these defined processes merely formalize good engineering practices and ask that the results be produced in a standard format. Sometimes these defined processes are a result of painful experiences on previous programs and represent a problem avoidance technique. Most of these processes are incorporated by referring to commercial and military standards rather than having bulky statements of work filled with repetitious detail.

Flight test community involvement in statement of work preparation is dictated by the need for contractor data during the development program including the flight test phase.

3.3 Design Reviews

The design review is a widely accepted program management tool used by the military and commercial sectors during the development process. The timing, content, and conduct of such reviews are normally detailed in the statement of work. Briefly, a design review is a meeting where the contractor presents the technical and programmatic status of the development effort. Before the actual meeting the contractor is often required to provide the customer with a considerable amount of technical material for detailed review. Again, such material content and delivery schedule is normally listed in the statement of work. The actual meeting then serves as a forum for the customer and provider to agree (or disagree) on the suitability of the evolving design.

The flight test engineering community should be well represented during the design review process. The information presented at reviews is essential to the flight test planning effort. As the design evolves, the flight test engineers must begin determining instrumentation requirements, data reduction needs and the flight hours required to adequately test the system.

Often the flight test engineers will again serve as a living repository of lessons learned (and endlessly

relearned). A current example originated with the B-1B aircraft. As originally designed, the B-1B had many warning tones built into the system. These tones were intended to alert the crew of impending problems. There were so many that the crew was unable to find the real fault. Consequently, crew work load was unnecessarily increased. At a subsequent design review a different contractor was presented a system very similar to the disorienting B-1B warning scheme. After learning of existing problems, the designers were convinced to change from tones to a voice warning system.

Often, flight test R&M engineers know what equipment offers the best reliability. A major weapons system was proposed to have a 10-year old design TACAN. The manufacturer was well pleased to learn of a new design that offered twice the reliability and weighed 25 pounds less.

During the conduct of design reviews the contractor is normally required to present documents to illustrate progress in developing the aircraft. From an R&M standpoint, the first of these is the R&M program plan. The plan is intended to show how the contractor intends to develop a reliable and maintainable system. With the current emphasis on R&M, the R&M plan is often part of the data submitted for source selection. Following source selection, the plan and updates are discussed at every design review.

While the program plan is a management document, the Allocations, Assessments, and Analysis report (often called the Triple-A or AAA) is a basic technical document. This report is a straightforward result of the systems engineering process that allocates reliability and maintainability requirements from the system or aircraft level downward to the subsystems, and finally, components. Table 3 is an example of an AAA report.

Another systems engineering result is the Failure Mode, Effects, and Criticality Analysis (FMECA). This report lists the ways that the system can fail and the result or impact on the system. Generally, requirements and common sense state that no single failure should result in the loss of an aircraft and the

Table 3
Example Allocations, Analysis, and Assessment Report
(Intermediate Level Maintenance [LRU] Task Time Predictions)

Line Replaceable Unit	Nomenclature Drawing Number	Failure Rate (per million hours)	Mean Corrective (minutes)
TPCC	7564358	815.08	25.68
MBC	377-6900-100	248.83	22.08
CEU	717135000	1,455.98	27.41
TPPS	717138000	215.78	14.26
ECU	734261	124.85	41.36
FINS	717212000	1,328.77	57.34
NPPS	717213000	158.43	145.27
NPCC	7564358	1,781.42	35.68
ANT/GIM	2677277	637.67	16.75
XMITTR	2711321	557.30	22.77
RCVR/EXCTR	2677331	545.23	10.57
RIU	2677351	749.99	7.64

FMECA is the analysis tool used to demonstrate (during the design phase) that the requirement has been met. Table 4 is an example of an FMECA.

The Association Europeenne Des Constructeurs De Material Aeroepatial (AECMA) has a standardized method of collecting R&M predictions from suppliers at the time of request for proposal. Figure 2 is a form used for providing reliability predictions and Figure 3 is an analogous form for providing maintainability predictions. These type of data are essential for updating AAA reports and FMECAs as suppliers are selected.

Both the AAA and the FMECA are important documents to the R&M engineering personnel and should be thoroughly studied before design reviews. Statements of work must provide for the reports to be delivered in time for careful engineering review (nominally 30 days). These documents should be examined for completeness appropriate to the stage of the development program. At the first or early reviews the contractor cannot be expected to have allocated reliability to the piece-part level nor considered all possible failure modes. On the other hand, once the design is frozen, drawings completed, and metal being bent, the reliability has obviously allocated by default if not by design.

Both the AAA and the FMECA should be examined for basic reasonableness (the so-called "sanity check"). If the contractor predicts far greater reliability than achieved for similar equipment the prediction must be questioned to learn what technological breakthrough led to the dramatic improvement. A tragic case of failure to properly question reliability predictions occurred with the U. S. Space Transportation System. The original prediction for the solid rocket boosters was one catastrophe failure in 10,000 uses. After the Challenger disaster, a historical review showed the past failure rate was 1 in 30 for large solid rockets.

During the actual flight test program the AAA and FMECA are necessary documents. As the reliability of individual components is measured, the results should be compared to contractor predictions to isolate those components in need of fixes and further development.

Another document that must evolve during the development process is the Logistics Support Analysis(LSA). As shown in the example in Table 5, the LSA lists, in exhaustive detail, the necessary information to support the weapons system. The extensive subject of logistics support can only be briefly discussed here. Even so, the flight test engineer must have an understanding of the contents and value of the LSA report. This report should evolve as the system is designed and should be the tool used to make the engineering tradeoffs necessary to develop an optimal system including the logistics "tail."

Flight test engineers must stay current on the evolving LSA to ensure that system- peculiar logistics features such as support equipment and facilities are available and tested concurrently with the air vehicle. Further, the LSA is the source of repair level information and plans. Repair level refers to what echelon of maintenance (on- aircraft, shop or depot) is the optimal level to repair failed parts. This planning is also called the maintenance concept. Much of this information is based on the contractor's estimates of reliability and maintainability, and as such, is subject to change when actual R&M performance data becomes available during the test program. As discussed previously, this refining or "fine tuning" is a major benefit from the test program.

A classic example of changing maintenance plans is from the E-3A Sentry program. During early deployment an expensive (U.S. $31,000) unit failed because of poor quality of a single small part. The unit was an electrical power filter and had no active parts. With only passive parts such as inductors and capacitors, the contractor predicted an essentially zero failure rate. With such a low failure rate, it is not economical to plan for or purchase the equipment needed to repair the filter. Because of the high cost, the 125-pound weight and the 200 man-hour replacement time, the failed filter was not discarded but saved as a curiosity item. Within the next month, six more filters failed. With U.S. $217,000 of throwaway parts, it was obviously time to change the maintenance concept.

During the different design reviews, the contractor should present data showing the environment predicted for the system components. As seen from Figure 1 the thermal and vibration factors hold the most interest for R&M engineers. Reliability predictions in the AAA report should be based on these predicted environments. When system components are essential for flight safety or mission performance, it is wise to instrument the system to verify that the actual temperature and vibration do not significantly exceed predictions. When the actual environment is different

Table 4
Failure Mode Effects and Criticality Analysis (FMECA)

COMPONENT: ANNUNCIATOR, AP/ATS WARNING
SUBSYSTEM: EFCS
SYSTEM INDEX NO.: 22-11-11
FAILURE RATE: 8.8 X10E-6/OPERATING HOURS

FUNCTION OF COMPONENT: ANNUNCIATES AUTOMATIC DISCONNECT OF AUTOPILOT AND/OR AUTOTHROTTLE SYSTEM
WUC: 57AL0
QPA: 2

FAILURE OR ERROR MODE	FAILURE CAUSE (INCLUDE OUTSIDE FACTORS)	EFFECT OF FAILURE (A) LOCAL (B) SUBSYSTEM (C) AIR VEHICLE, INIT	(A) INDICATION TO FLIGHT CREW (B) OTHER FAILURES WITH SAME INDICATION (C) HOW DOES FLIGHT CREW ISOLATE THE FAULT? (D) CORRECTIVE ACTION (FLIGHT CREW) (E) EFFECT OF LIKELY INCORRECT ACTION (F) IS FAILURE PREDICTABLE? HOW? (G) HOW DOES MAINTENANCE CREW ISOLATE THE FAILURE? (H) CORRECTIVE ACTION (MAINTENANCE CREW)	LEVEL OF SEVERITY
1) AP (OR ATS) ANNUNCIATOR WILL NOT LIGHT (PILOT SIDE OR CO-PILOT SIDE)	A) BROKEN INPUT OR B) NO VOLTAGE FROM ANNUNCIATOR DIMMING OR NO FAIL DISCRETE FROM 2 FCCS OR D) BOTH BULBS BURNOUT	A) NO LIGHT ON PILOT (OR COPILOT) AT (OR ATS) ANNUNCIATOR B) NO LIGHT ON PILOT OR COPILOT AT (OR ATS) ANNUNCIATOR C) NONE	AUTOPILOT ON -- A) AURAL WARNING BUT NO LIGHT ON 1 OF 2 ANNUNCIATORS (PILOT OR COPILOT) B) NONE C) COMPARE PILOT AND COPILOT ANNUNCIATORS - VERIFY OFF POSITION OF AP OR AT AT SOL. HELD SWITCH ON AFCS CP- D) USE OPERATIVE INDICATOR E) N/A F) NO G) ACCESS FCC BIT VIA MCD/MCK H) REPLACE DEFECTIVE PART -- SCAS ON OR SCAS OFF -- N/A	IV
2) AP (OR ATS) ANNUNCIATOR ILLUMINATED CONTINUOUSLY (PILOT SIDE OR COPILOT SIDE)	A) HOT SHORT TO INPUT WIRE B) FAULT IN ANNUNICATOR DIM. UNIT CAUSES CONTINOUS OUTPUT	A) PILOT OR (CO-AT (OR ATS) ANNUNCIATOR STAYS ON B) PILOT OR COPILOT AT (OR ATS) ANNUNCIATOR STAYS ON C) NONE	AUTOPILOT ON -- A) LIGHT ON 1 OF 2 ANNUNICATORS (PILOT OR COPILOT) BUT NO AURAL WARNING B) NONE C) COMPARE PILOT AND COPILOT ANNUNICATORS - VERIFY ON POSITION OF AP OR AT SOLENOID HELD SWITCH ON AFCSCP D) USE OPERATIVE INDICATOR E) N/A F) NO	IV

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<table>
<tr><td rowspan="2">1 VENDOR:</td><td colspan="2" rowspan="2">2 EQUIPMENT DESCRIPTION:</td><td colspan="3">3 PART No:
FEDERAL SUPPLY CODE:</td><td rowspan="2">4 SPECIFICATION:</td><td rowspan="2">6 BASIS OF PREDICTION:</td></tr>
<tr><td colspan="3">5 DRAWING:</td></tr>
<tr><td colspan="6" rowspan="4">7 FUNCTIONAL DIAGRAM(S):</td><td colspan="2">8 FAILURE RATE, total (Failure/10^3 h or cycles)</td></tr>
<tr><td>FLIGHT OP.</td><td></td></tr>
<tr><td>GROUND OP.</td><td></td></tr>
<tr><td>GROUND NON-OP.</td><td></td></tr>
<tr><td rowspan="2">9 FUNCTIONAL DIAGRAM BREAKDOWN</td><td rowspan="2">10 FAILURE MODE:</td><td rowspan="2">11 ITEM ON DIAGRAM</td><td colspan="3">12 FAILURE RATE, in detail (Failure/10^3 h or cycles)</td><td rowspan="2">13 EFFECT ON EQUIPMENT</td><td rowspan="2">14 INDICATION HIDDEN FAILURE</td></tr>
<tr><td>FLIGHT OPERATION</td><td>GROUND OPERATION</td><td>GROUND NON-OP.</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
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Figure 2 AECMA Supplier Reliability Prediction

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1 VENDOR:	2 EQUIPMENT DESCRIPTION:	3 PART No: FEDERAL SUPPLY CODE: 5 DRAWING:				4 SPECIFICATION
6 INSTALLATION DRAWING:	7 No PER A/C:	8 WEIGHT:	9 DIMENSION:		10 SERVICE LIFE:	
"ON A/C MAINTENANCE"	11 TASK DESCRIPTION:	12 TIME BETWEEN MAINTE-NANCE	13 MAINTENANCE TIME: ACTIVE MAINTENANCE TIME:	DIRECT MANHOURS	14 DIRECT MAINTE-NANCE MATE-RIAL COST:	15 FACILITIES: SPECIAL TOOLS: TEST EQUIPMENT:
LINE MAINTENANCE: — Scheduled						
— Unscheduled						
SCHEDULED REMOVAL:						
UNSCHEDULED REMOVAL:						
"OFF A/C MAINTENANCE" TEST:						
OVERHAUL:						
REPAIR:						
STORAGE LIFE:						

Figure 3 AECMA Supplier Maintainability Prediction

Table 5
Logistics Support Analysis
(U.S.A. Military Standard 1388-1A/2A)

Operations & Maintenance Requirements

- Identification of hardware, source, and quantity required
- Frequency and duration of use
- Allocation of preventive and corrective maintenance needs between organizational, intermediate and depot levels
- Availability requirements

Item Reliability and Maintainability Characteristics

- Identification, source, and quantity required
- Availability requirements
- Maintainability considerations
- Function of item
- Maintenance concepts and qualitative maintainability requirements

Failure Mode and Effects Analyses

- Failure modes and resulting effects
- Damage mode and resulting effects
- Survivability and vulnerability analysis

Criticality and Maintainability Analyses

- Criticality analysis
- Maintainability analysis
- High risk item identification

Operation and Maintenance Task Summary

- Identification, source, and quantity required
- Maintenance task, level, time required, manning skills, support equipment needed

Operation and Maintenance Task Analysis

- Identification, source, and quantity required
- Task Identification and description, time required, skills
- Common/special tools, parts, and material required for task

Personnel and support requirements

- Training requirements, personnel, support equipment, and supply support requirements per task

Support Equipment & Training Material Description

- Identification, source and quantity required
- Size, weight, storage volume, and costs
- Functions to be performed
- Characteristics and installation factors
- Justification for new material/skill requirements

Unit Tested/Automatic Test Program/Training Material Description

- Test program set elements
- Hardware and software required for testing

Facility Description

- Identification and description of new facility
- Functions and tasks to be performed
- Requirements, design criteria, lead times, construction, and required utilities
- Facility utilization rate and cost justification

Skill Evaluation and Justification

- Identification, source, and quantity required
- Skill specialty codes
- Functions to be performed
- Additional skill and training requirements
- Selection criteria (physical, mental and educational)

Support Items Identification

- Spare parts data
- Provision screening data
- Packaging data

Transportability Engineering

- Identification of transportability requirements

from the expected, the predicted reliability must be recalculated and changes made.

3.4 Flight Readiness Reviews

In the near term, before the aircraft's first flight, it is normal practice to hold a series of meetings to assure that the vehicle is ready for flight. The contractor presents the results from the laboratory and qualification testing on subsystems and components. This information is the first real reliability data and often the first sign of impending problems. The flight test community should be well aware of any problems encountered and the potential impact on safety of flight. Further, all flight essential equipment must be tested in some manner and to the largest extent possible. Any failures of flight essential equipment must be corrected or have acceptable work-around procedures established. Mockups, "iron birds," and environmental test chambers are some of the tools used to increase confidence in flight readiness.

While reliability data from test chambers and fixtures may not represent the aircraft, it is still very useful. All failure modes experienced in flight critical equipment must be analyzed and a conscious decision made as to the necessity of a fix.

4.0 TEST PLANNING

4.1 General

"Well begun is half done." This is never more true than with the test planning process. Initially, test planning will be necessarily general in nature and continuously refined as the aircraft approaches first flight. Planning must begin early in the development cycle to ensure that all needed resources are available at the beginning of flight test. Resources needed include personnel, test assets, maintenance, operations, and instrumentation data, and data reduction tools.

4.2 Personnel

Appropriate numbers of correctly trained people from several backgrounds are required to conduct a flight test R&M evaluation. Obtaining and training people is a long-lead time process and must begin early in the development cycle. Ideally, these individuals should have participated in the design review process prior to actual flight test. Such participation will provide detailed knowledge of the aircraft to be tested and some feeling for potential trouble areas. An excellent example comes from the ground-launched cruise missile. During the design review process, it became obvious that the gas turbine driven electrical generators used to power the control complex and launcher were going to be a reliability problem. As a result, work-around methods and improvements were developed before the beginning of test.

Trained R&M engineering personnel are essential to a flight test R&M evaluation. The engineers should have a strong background in aircraft and aircraft systems in addition to training and experience in the principles and practice of R&M. Perhaps the ideal R&M engineers are those individuals that have an in-depth expertise in one discipline and good working knowledge of many others involved in aircraft engineering. The number of engineering personnel needed is a direct function of the complexity of the system being tested. For small systems, such as a primary trainer with minimal avionics, one engineer should suffice. Complex aircraft, such as a bomber or large cargo carrier might require as many as five engineers. Table 6 lists the duties performed by these engineers.

Table 6
Flight Test R&M Engineer Duties

- Participate in preparation of requirements documentation.
- Participate in design and technical reviews.
- Prepare test plans and test information sheets.
- Determine instrumentation requirements.
- Implement R&M data collection system for flight test.
- Classify test R&M data as to criticality, etc.
- Obtain failure analysis from contractors and vendors.
- Analyze R&M data to identify high-failure rates and high manhours consumers.
- Monitor throwaway parts to identify deficiencies with low cost items.
- Observe maintenance to identify deficiencies in fault isolation, component replacement, repair verification, and support equipment.
- Verify effectiveness of implemented design changes.
- Write deficiency reports.
- Write intermediate and final technical reports.
- Write lessons learned documentation.

Staffing a test program with maintenance personnel poses a dilemma. From one viewpoint it is desirable to have senior maintenance personnel available to gain from their experience with other aircraft and to have these personnel judge the suitability of maintenance issues. In contrast, it is necessary to determine how well the aircraft can be repaired and serviced by the average maintainer. An acceptable compromise is to have junior people do the actual work while the senior people observe and judge. In this manner, the experienced people can note the mistakes, trials and tribulations of the average maintainer, and develop improvements when needed. This requires that maintenance personnel be assigned on a selective basis and that experienced people be made available on a continuous basis even though they are not maintaining, but rather testing the system. The actual number of maintenance personnel needed varies greatly with the complexity of the system. As a minimum, each technical specialty (such as engine mechanics and avionic technicians) should be represented by at least one experienced individual.

Experienced flight crew personnel are also needed during an R&M evaluation. When an inflight anomaly occurs, they must accurately report the problem and the situation of the aircraft when it occurred. The complete observance and accurate reporting is essential to finding and correcting problems. In many ways the ability to observe and report differentiates the test pilot from the operational or line pilot. The flight crew must also assist in determining if the anomaly had any implications for flight safety and if the problem prevented completion of the aircraft mission. This requires that the aircrew have operational experience with the intended mission of the system. It also requires that the aircrew have a detailed knowledge of the new aircraft and the development effort. The best way to gain such knowledge is participation in design reviews.

An often neglected yet important system facet is depot maintainability. While it is not possible to take a test aircraft to a repair depot during flight test, it is possible to bring experienced depot personnel to the test site. Because the depot has a wide variety of technical specialties it is usually most cost effective to have different specialists participate in flight test on a temporary basis. They should be temporarily assigned to the test program long enough to evaluate their area of expertise in some depth. A good example occurred during the prototype testing of a tactical transport. The depot maintenance landing gear expert noted that the type and process used for plating the main gear strut was very difficult to remove when replating was required. A more suitable plating was no more costly and the change was made.

One final personnel consideration is assignment stability. It is essential to keep the same people throughout the acquisition process. It does little good to have test personnel participate in the early part of the process, such as design reviews, and then change jobs prior to the first flight. This is a particularly acute problem in many military organizations where periodic reassignment is standard procedure. Every effort must be made to maximize personnel continuity. This often requires the liberal use of civilian personnel in key positions when military personnel assignment stability cannot be assured.

4.3 Test Asset Requirement

The single most important test program cost driver is the number of flight test hours. Then the single question becomes: "How many flight hours are required to accomplish an effective R&M evaluation?". The answer to that question varies in direct proportion to the complexity of the aircraft being tested. A simple aircraft such as the U. S. Air Force T-46 can be well characterized, and a majority of the R&M problems identified in about 700 flight hours. In contrast, a large aircraft with complex avionics, such as the B-1 bomber, may require several thousand flight hours to test. In either case, it is not cost effective to test the aircraft long enough to accurately measure the reliability of every part. Indeed, even avionic components with a 2,000-hour meantime between failure (MTBF) cannot be measured with any statistical significance. But, an avionic system, such as a 100- hour MTBF radar can be measured. Even in the case of the 2,000-hour MTBF component, the initial reliability will be much lower (200 to 400 hours typically). The flight test program can measure the lower numbers and identify some of the corrections needed to achieve the desired 2,000-hour MTBF. Considering the large differences between predicted reliability and that eventually achieved, the test program seldom affirms reliability, but rather often denies reliability. That is to say, test results usually show a much lower reliability than was predicted.

Normally, no flight test time is dedicated to R&M evaluations. Instead, the test program is structured around the flights required to test the vehicle and

subsystem performance characteristics. Table 7 shows the number of flight test hours for several aircraft. Then, as a result of stressing the vehicle during test, much failure and repair data are available. There are several considerations that can maximize the resulting R&M data. First, all installed subsystems should be operated every flight regardless if it is needed for any given test. This will maximize the operating experience on the subsystems. To fix ideas, consider aircraft cruise performance testing. Much flight time is needed to gather fuel consumption data throughout the airspeed/altitude envelope. During that time, very little of the aircraft avionic suite is essential to that testing. However, the full avionic suite should be operated throughout performance testing to increase resulting R&M data. This operation must include turning the subsystems on and periodically testing those equipment during the mission. This may be done by including the appropriate directions in the flight crew checklists and flight cards.

Table 7
Flight Hours for Initial R&M Evaluation

Aircraft	Hours
A-7D	900
A-10A	1,325
C-5A	2,700
C-141A	2,500
F-4E	700
F-5A	845
F-15A	2,900
F-16A	1,950
F-16C	1,345

Missile testing offers a similar opportunity to increase the R&M experience base. For every test mission, the carrier aircraft should be loaded with a full complement of missiles, not just the one missile needed for that day's test. In this fashion, the available R&M database can be increased substantially. This requires advanced planning in order that a sufficient quantity of missiles is available to the test effort. This advanced planning and the cost of early missile delivery is often much cheaper than attempting to duplicate the flight environment in some ground test rig to gain the needed reliability data.

While little or no flight time dedicated to R&M evaluations, much ground time is required for maintainability demonstrations and logistics evaluations. Although much maintainability information can be obtained from normal maintenance, most flight test programs do not last long enough for all (or even a significant sample) of maintenance tasks to arise. For this reason a block of ground time should be set aside to demonstrate those interesting tasks that have not naturally occurred during the test program. The tasks of the most interest are the long duration, complex efforts. These maintenance tasks might use unique support or test equipment that needed to be tested for functional adequacy. This dedicated block of ground time varies in duration as a function of the aircraft complexity. A simple primary trainer such as the T-46 should not require more than several weeks while a vehicle as complex as the B-1A bomber might require months.

4.4 R&M Data Requirements

The three principal R&M data sources are flight crew debriefings, maintenance records and aircraft special instrumentation. Flight crew debriefing provides a measure of usage (flight time) and a record of pilot-noted problems. Maintenance records report all resources needed to maintain the vehicle in mission-capable condition. The aircraft special instrumentation records assorted measures for postflight analysis. These three data sources and the required data reduction are discussed separately.

4.5 Flight Crew Debriefing

The most readily obtainable stress data are aircrew debriefing information. Because of the relative ease of use, many test programs rely solely on this data as stress measurement. Figure 4 shows an aircraft debriefing record used for the F-111 test program. The first line of the form is for identification information such as: date, time, and mission number. The second line of the form is for time of stress data such as flight duration and time in afterburner. Also included are data about cyclic stresses such as wing sweeps and landings. The grided area and corresponding table record, in a rudimentary fashion, the dynamic pressure induced stresses seen by the airframe. Other cyclic uses of different equipments should also be recorded. It should

F-111 MISSION DEBRIEFING

CARD NR	MISSION IDENTIFICATION DATA							
1	1. MISSION NR	2. ACFT NR	3. DATE (DAY MO YR)	4. TYPE MSN	5. SCHED TO (HR MIN)	6. ACTUAL TAKEOFF (HR MIN)		
	7. SCHED DURATION (HR MIN)	8. ACTUAL DURATION (HR MIN)	9. HIGH MACH	10. HIGH ALT	11. SUPER-SONIC TIME (HR MIN)	12. LH AB TIME (HR MIN)	13. RH AB TIME (HR MIN)	14. NUMBER LANDINGS / 15. WING SWEEPS
	16. AIRCRAFT COMMANDER			17. PILOT/ENGINEER				

FLIGHT PROFILE

ALT FT MSL (X 10^{-3})

60, 50, 40, 30, 20, 10, 0

CARD NR												
2	PHASE CODE	B	C	D	E	F	G	H	I	J	K	L
	PHASE OF FLIGHT	START & PRE-TAXI	TAXI	TO AND ACCEL	CLIMB	CRUISE		COMBAT & WPN DEL	RETURN		TRAFFIC PAT & LANDING	TAXI & SHUT DOWN
	TIME OF DAY	18.	19.	20.	21.	22.	23.	24.	25.	26.	27.	28.
3	AVERAGE MACH				29.	30.	31.	32.	33.	34.		
	AVERAGE ALTITUDE					35.	36.	37.	38.	39.		

MISSION OBJECTIVE	PERCENT SUCCESS

REMARKS

AFFTC FORM APR 66 0-294 PREVIOUS EDITION OF THIS FORM IS OBSOLETE. PAGE 1 OF 8 PAGES

Figure 4 F-111 Test Program Debriefing Form

be noted some of that cyclic data may suffer in accuracy by depending on aircrew recording or memory. Speed brake cycles is a good example. No pilot can be expected to accurately count speed brake usage during simulated air combat maneuvers. In cases where accuracy is important, instrumentation should be used to record cyclic use.

In addition to usage , the aircrew should also note any anomalies that occur and when they occurred in the flight. This information must be complete enough to allow maintenance to diagnose the problem and to allow R&M engineers a full understanding of the possible failure. The aircrew must also record any anomalies reported by the aircraft built-in-test system and note whether any related symptom was observed. Newer automated recovery systems provide health diagnostics information for postflight analysis. It is still a good idea to debrief the aircrew to identify what anomalies were observed and during which portions of the flight envelope.

As the program progresses through the design review phases, the R&M test engineers should continuously refine their requirements and plans for flightcrew data. Aircrew debriefing forms should be developed jointly by aircrew and engineers.

Debriefing data from aircrews is the simplest information to convert to usable form. These data are normally a single sheet or two per attempted sortie. The easiest way to aggregate and summarize these data are with the use of desk top computers and a commercial database management system. The most commonly used data summary lists the accumulated stress (flight hours or cycles) per unit time (often months).

4.6 Maintenance Data

A considerable amount of information is required from the maintenance personnel. Aircraft maintenance can be considered in two broad general categories; scheduled and unscheduled. Scheduled maintenance is those maintenance efforts whose need can be foreseen and accomplished in a planned manner. Aircraft servicing and inspections comprise the bulk of this type maintenance. Data on scheduled maintenance are needed to measure the resource requirements for such efforts and to determine the time the aircraft is not available for "revenue service" because of the need for such maintenance. Such scheduled activities should be accurately measured early in the test program. The exact procedures used can be studied for possible optimization to limit resource consumption and out of service time. When no further optimization is possible, data collection for scheduled maintenance can be discontinued.

Unscheduled maintenance is that maintenance required to restore the aircraft to operating condition after an anomaly. Data on unscheduled maintenance are needed to again measure resource requirements, to determine aircraft nonavailability and also to determine the exact cause of the anomaly. In addition to the on aircraft work done, these data must include the "off-aircraft" work. That is, all work necessary to isolate the exact cause of the anomaly and restore normal operation must be included. During test programs the acquiring service often does not have the capability to repair the new equipment and failed equipment must be returned to the prime contractor. Then the prime contractor may return the failed item to a vendor or even lower tier supplier. Considerable planning is needed to insure that, regardless of the complex repair path, the needed information is available to the flight test engineers.

History shows that the best way to insure that the needed data are available is to specify the requirement in the original contract and state that the requirement is to be levied on all vendors and lower tier suppliers. Some experienced contractors routinely require vendors and lower tier suppliers to provide repair data and failure analysis. Those contractors regard this process as simply good commercial practice. This is not always the case. The recent B-1B flight test program was initially plagued with continuing nuisance hydraulic leaks from a type of coupling used throughout the aircraft. Many months and much hydraulic fluid passed while a series of discussions was required to convince the contractor to take any action. Eventually the contractor returned several leaking couplings to the coupling supplier. Within days the supplier responded by acknowledging responsibility for the problem and stating what action they would take to correct the defects. Much maintenance time and valuable flight test time could have been saved if the prime contractor had an established procedure to return failed parts, even those considered nonrepairable, to the original supplier.

A classic case involved a magnetic tape cartridge used to transfer mission data to the aircraft. During laboratory and flight test over 100 of the tape cartridges failed and the prime contractor did not return any of the

cartridges to the supplier. The supplier only found out about the problem when they questioned why the prime contractor was ordering so many replacement tape cartridges. Again, once the supplier became aware of the problem the defect was fixed in a matter of days.

The information needed about aircraft maintenance varies somewhat with the individual program, but generally the same basic information is needed. Appendix A lists the individual data elements and discusses the use of such information.

Historically, this data are difficult to obtain from contractors after a development contract has been signed. The requirement for such data must be included in the basic contract if the contractor is to perform maintenance during the flight test program. This requirement was inadvertently omitted from the B-1B development contract and the airframe contractor submitted a U.S. 3.2-million dollar proposal to provide the data. Better planning would have prevented that problem.

4.7 Maintenance Data Processing

The reduction of maintenance data is a much more challenging task because of the greater relative volume, more sophisticated database creation and complex data analysis requirements. The volume of maintenance data is such that desktop computers are suitable for the small test programs only. For example, the F-111 Digital Flight Controls System test program was conducted using a desk top computer to store and analyze maintenance data. However, data collection was limited to three line replaceable units (LRUs-commonly called "black boxes"). Further, the test program was only 600 flight hours duration.

Because desk top computers are unsuitable, a large "mainframe" computer is needed to store and process the maintenance data for large test programs. The C-5A maintenance database was 200 million bits of information at the end of the test program. This also requires fairly complex software to maintain and analyze this amount of data.

The software needed to create and maintain a maintenance database varies depending on the information and format of the raw data, but certain general requirements exist. For example, as part of the database maintenance process, the times that aircraft maintenance started and stopped must be converted into man-hours, active hours and elapsed hours. All individual maintenance actions (such as troubleshooting, actual repair and cleanup) must be linked together into a single maintenance event. Further, all levels of repair (on-aircraft, off-aircraft and depot) must be linked together. This complex linkage is needed because the various actions within a single maintenance event often occur at different times and different places. When all the smaller actions are properly linked, the total repair cost, both time and material, are visible. When properly done, the data base should provide an audit trail that begins with a description of the aircraft problem and concludes with action taken to prevent recurrence of that problem. Table 8 is a much simplified example of this. The linkage process is the most difficult part of R&M data processing.

Maintenance data analysis computer reports vary from the trivial to the almost unusably esoteric. Generally, the value of these reports is inversely proportional to the complexity. A most usable report, simply lists the most frequently occurring failures in descending order of frequency. A report of similar type for the highest maintenance man-hour consumers is also of utility. Table 9 summarizes other computer analysis reports of varying utility.

4.8 Failure Analysis

Another type of information that must be obtained from the contractor is the detailed analysis describing the root cause of failure (sometimes called physics of failure). This type of analysis is essential. Both contractor and customer should plan to perform such analysis for every failure that occurs during the flight test program. This includes failures of nonrepairable pieces. Without knowledge of the causes of failure it is impossible to prevent reoccurrence. Again, this information is costly to obtain after the contract is awarded and must be included in the earliest contracts. The prime contractor must be required to levy this requirement on all vendors and lower tier suppliers.

4.9 Instrumentation Data

For avionics, temperature and vibration are normally considered the primary causes of failure with changing levels of thermal and vibratory stress causing different failure rates. Table 10 shows the MTBF for the U.S. Air Force standard TACAN (AN/ARN-118) in several different aircraft. The greater than one order of

Table 8
Maintenance Action Audit Report

AIRCRAFT: F-15E **SERIAL**: 9100015 **FLIGHT HOURS**: 348

WORK UNIT CODE: 74JA0 **REPORT#** 006501 **DATA CODE**: 3

WHEN DISCOVERED: INFLIGHT **HOW MALFUNCTIONED**: INTERMITTENT

PROGRAM DESCRIPTION VSD (VERTICAL SITUATION DISPLAY GOES BLANK WITH AIRCRAFT VIBRATION SUCH AS SPEED BRAKES OR FLAPS. RSETS OK AFTER BEING OFF SEVERAL SECONDS.

FLIGHT LINE MAINTENANCE TROUBLESHOOT VSD SYSTEM. REMOVE/REPLACE VSD. SYSTEM OPS CHECKS GOOD.

FAILED ITEM:	VSD	**SERIAL#**:	00041611	**ETI METER**:	0095
INSTALLED ITEM:	VSD	**SERIAL#**:	00001233	**ETI METER**:	0085

SHOP MAINTENANCE: REMOVE/REPLACE X DEFLECTION AMPLIFIER (2A3). VSD OPS CHECK GOOD. AMPLIFIER NOT REPAIRABLE THIS STATION. RETURN TO VENDOR FOR FIX, FAILURE ANALYSIS AND CORRECTIVE ACTION.

FAILED ITEM:	2A3	**SERIAL#**:	00208004	**ETI METER**:	0095
INSTALLED ITEM:	2A3	**SERIAL#**:	00208018	**ETI METER**:	0028

VENDOR ANALYSIS: DISCREPANCY CAUSED BY POOR SOLDERING. SOLDER REFLOWED AND UNIT CHECKS GOOD. INVESTIGATION REVEALED THAT SOLDERING WAS DONE BY AN ENGINEER VICE SOLDERING TECHNICIAN. VENDOR STATED SERIAL NO. 4 WAS ONLY UNIT HARMED. ALSO PROMISED ENGINEER WOULD NOT REPEAT ACTION AND THAT NEW QA PROCESS WOULD DETECT ANY SOLDERING PROBLEMS. USAF INSPECTION OF ALL DELIVERED UNITS FOUND NO OTHER PROBLEMS. ACTION CLOSED.

Table 9
Computer Analysis Reports

REPORT	CONTENTS AND USAGE
Maintenance Event Audit Report	Lists all actions necessary to repair the system and eliminate the defect. Used to trace process from aircraft repair to depot or vendor and ensure needed changes are accomplished.
Top Failing Items	Lists in rank order the most frequently failing items. Used to ensure that weak parts receive corrections.
Top Maintenance Hours Users	Lists in rank order the parts that consume the most labor hours. Used to find areas for potential maintainability improvements.
Maintenance Manhour per Flying Hour	Calculates MMH/FH by subsystem and system. Used for contractual requirements verification and manning needs predictions.
Active Manhours Summary	Calculates meantime to repair (MTTR) at component, subsystem and system level. Used to verify achievement of contractual requirements and input to availability models.
Component Discrepancy	Calculates meantime between failure (MTBF) for component, subsystem and system. Used to verify achievement of contractual requirements and as input to spares requirements models.
Reliability Growth	Plots MTBF as a function of test time. Used to assess and predict reliability.

Table 10
TACAN (AN-ARN-188) Reliability by Aircraft
(Data from the U.S. Air Force Logistics Command Databases of the 1984 to 86 Time Period and Sample Revalidated for the 1989 to 90 Time Period)

Aircraft	Meantime Between Failure (hours)
F-4G	199
FB-111A	410
A-10A	774
F-111E	818
F-16C/D	3,296
A-7K	592
F-15C	685

magnitude difference between the F-4G and F-16D aircraft clearly shows the importance of the environment in determining equipment reliability.

Because of the high cost of instrumentation, R&M test engineers seldom, if ever, get all of the measurands that they want. The problem then becomes an allocation process. With a limited capability to instrument the test aircraft, where should instrumentation transducers be placed to maximize the value of the information? The problem becomes more acute when instrumentation is to be installed during initial aircraft construction. This means that the instrumentation must be specified in parallel with the aircraft design effort. The obvious rule of thumb is to instrument the most critical from a safety of flight standpoint and from a cost viewpoint. Less obvious perhaps is the approach of instrumenting the system to verify the design predictions. Many aircraft temperature predictions are made based on results of a large computer model of the system. Instrumentation should be designed to verify and perhaps improve the model.

Vibration sensing instrumentation is more difficult to plan. The only guidelines are to consider all vibration inducing sources and place sensors around those producing sufficient energy to be potentially troublesome. Aircraft mounted guns are always a good candidate for vibration sensors because of the very high energy generated. Equipment mounted close to such energy sources should be closely monitored for vibration. Engine and accessory power unit mounted equipment may produce considerable energy.

One lesson endlessly relearned is the need to thoroughly understand the vibration environment of externally mounted equipment. While external pods often seem like a good way to enhance capability and adapt aircraft for special missions, the vibration encountered can be quite severe. Other nonaerodynamic additions to a basic aircraft also induce similar problems.

Predicting vibration levels of such externally carried equipment remains a very inexact science. The only current solution is construction and test of a structurally representative article very early in the development cycle. These test articles must be aerodynamically and structurally similar to the planned equipment. These test "shapes" must have enough instrumentation to completely characterize the vibration environment at the worst case flight conditions. Most importantly, these "shapes" must be tested on all potential carrier aircraft. In case after case, missiles and external pods are designed for one aircraft and adopted to others. It is somewhat ironic that the more successful a new missile or pod, the more likely the user will want to use it on other, perhaps unsuitable, aircraft. The resulting vibration data must be available to the designers to ensure it is suitable for the actual environment. These structural test articles can also be used to gain other needed data such as incremental drag, changed handling qualities and flutter characteristics. The resulting vibration data must be available to the designers to determine if the missile or pod is suitable for the intended operational environment.

In all cases, optimal selection of instrumentation requires considerable engineering judgment. It is relatively easy to select instrumentation after thermal or vibration problems arise; the difficulty comes in predicting instrumentation needs during the aircraft design phase. As the program progresses through the development process, the R&M engineers, along with thermal and vibration specialists, should continuously refine their instrumentation requirements.

4.10 Instrumentation Data Processing

Complex tools are also needed to reduce special instrumentation data to usable form. Engineers from many different disciplines normally share these tools. This means that R&M engineers have help on the

planning process. But, the R&M engineering interests are different than other disciplines and the R&M people must be fully involved in the planning process to make certain that their unique requirements are addressed. In the recent past large mainframe computers where used almost exclusively. The current trend, however, is towards smaller machines such as engineering workstations for at least part of the task. Much has been written, in AGARD volumes and elsewhere, on the process of converting raw instrumentation data into engineering units. This treatise will rely on that previous work. Once the instrumentation data are available in engineering units form, the flight test R&M engineer must select and present the appropriate environmental data in a suitable form. The two most important aspects of environmental data are thermal and vibration and will be discussed separately.

Planning must ensure that data reduction tools have the capability to present information in the formats needed by R&M engineers. Most thermal data have the advantage of requiring a low sample rate because of the slow rates of temperature change of any object with noticeable mass (and resultant high thermal inertia). The problem in dealing with thermal data from aircraft is that a given temperature may be a function of many variable such as airspeed, altitude, ambient air temperature and throttle setting. As with aircraft performance parameters, thermal data must be corrected to "standard day conditions" where possible. If correction is not possible (usually because of the lack of a thermal model), the data must be presented with all conditions and caveats noted.

When the aircraft has a specific design mission it is possible to show the temperatures throughout the mission. This technique is useful if a reliability problem is thought to be temperature induced. Another useful tool is the temperature mapping technique. Here, the specific temperature is mapped throughout the aircraft envelope. A considerable amount of data, usually from many flights, is required but the results are eloquent and portray much information in a compact form. Here, different characters are used to show different temperature ranges. The engineer must carefully select the temperature ranges to be shown. For example, below critical temperatures, a single character might represent a wide range of values. That is, one symbol could be used to indicate that the measured temperature is in a region of indifference or, at least, in a satisfactory state. Above satisfactory temperatures, different symbols should be selected to show severity of problems. Normally this means using increments of 10 degrees Celsius. If color media is available, the problem with displaying discrete increments vanishes.

Both of these presentation techniques are suitable for use on an engineering work station when the data are available in engineering units. Because of the cost, in both instrumentation and engineering man-hours, these techniques are generally limited to suspected problems, high cost items and safety of flight issues.

Vibration data requires a very high sample rate and is correspondingly more difficult to reduce. Again, engineering workstations are being used once the raw data are converted to engineering units. As with temperature, vibration levels change with a number of variables. Generally, it is important to know the peak, or worst case vibration level and a measure of the average level. A common data presentation scheme is to plot peak acceleration as a function of frequency. Figure 5 is an example. A second technique is called a power spectral density (PSD) plot. Here, the acceleration squared divided by the frequency is plotted as the abscissa while the frequency is plotted as the ordinate. Because vibration is often related to the dynamic pressure on the aircraft, a third method plots acceleration versus dynamic pressure. The example shown in Figure 6 uses the common English units (pounds per square foot). This particular method has the advantage of eliminating several variables but requires more data reduction effort.

As with thermal data, the associated costs often prohibit analysis of vibration data except for suspected problems, high cost components and safety of flight issues.

4.11 Safety

Safety must be a primary consideration for all flight test activity. Although R&M evaluations are not the most hazardous tests conducted, safety is still very worthy of concern. Quoting in part from AGARDograph AG-300-Vol. 8: "The secret to accident prevention is anticipating personnel mistakes, equipment malfunctions and environmental aberrations which change hazards -- to accidents." Like R&M, safety is a designed-in characteristic. Failure to design-in safety leads to the need for procedures and equipment to assure safety. Climatic extremes exaggerate hazards. Again quoting from AG -300-Vol. 8: "Working around

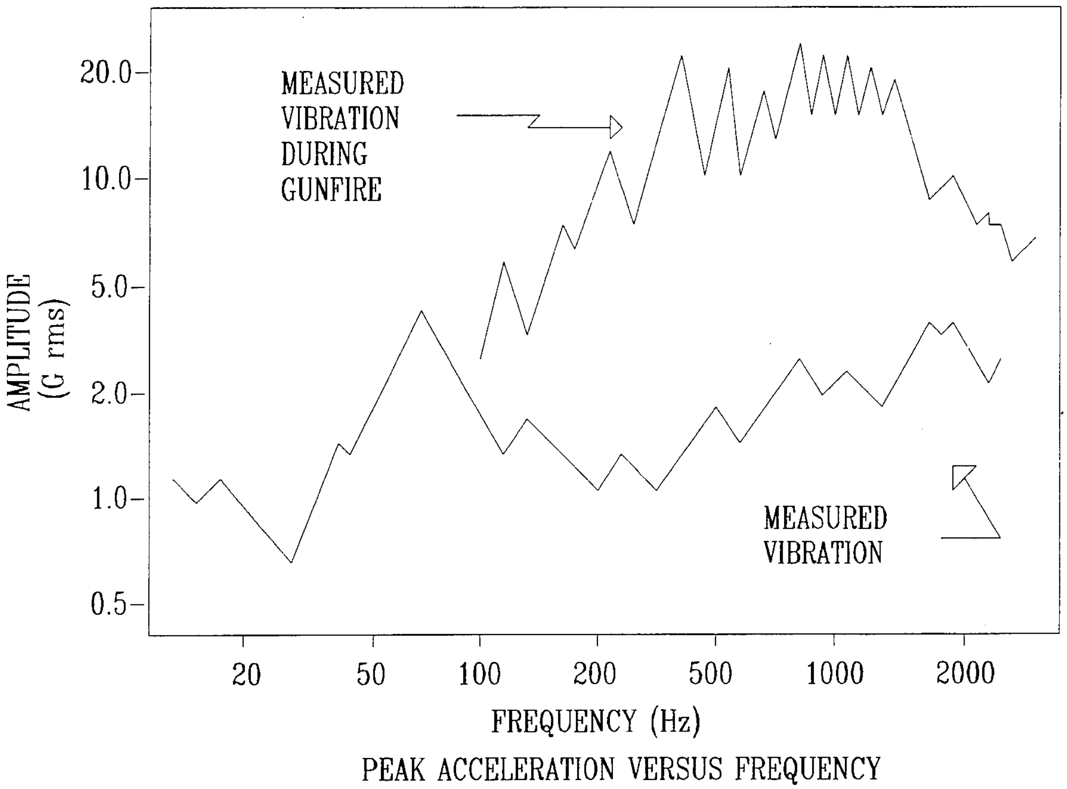

Figure 5 Peak Acceleration Versus Frequency Sample Plot

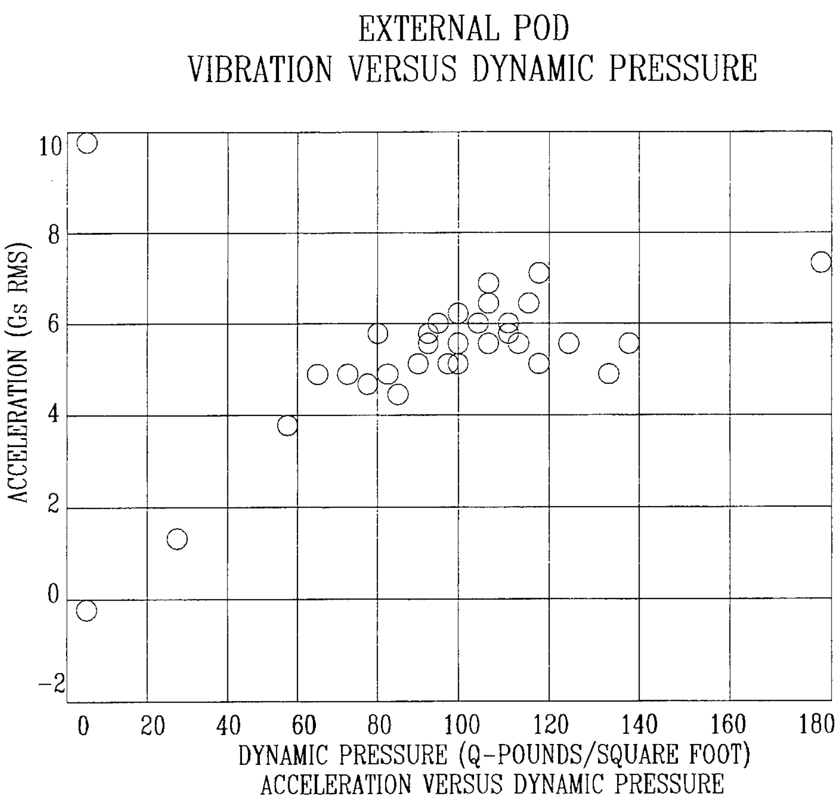

Figure 6 Acceleration Versus Dynamic Pressure Sample Plot

as well as operating a flight vehicle in extreme climatic conditions compounds hazards and demands constant attention to safety. Like flight itself, extreme or adverse environmental conditions are unforgiving of the ill-prepared, the complacent and the uninformed."

A relatively common R&M test that requires particular attention to safety is the quick-turn demonstration (also called a hot turn). This demonstration, and the development leading to it, is intended to measure the minimum time between recovery from one sortie and launch for the next sortie. For fighter aircraft this means simultaneous refueling and weapons reload. For these type demonstrations, safety considerations are essential. Before the total demonstration is attempted, each subpart should be completed many times. Once each subtask is optimized for time and safety, then the total effort should be walked through and carefully studied. In the interest of safety, most of the subtasks should be simulated during these walk throughs. For example, a fuel truck should be positioned as planned for the real quick turn. The refueling hose should be correctly placed and connected and disconnected at the appropriate points in the walk throughs, but fuel should not be transferred until enough walk throughs have been performed to assure that safety is not compromised.

Quick turns and other R&M tests or demonstrations with a potential safety impact should always be accomplished in this "build- up" manner. This means that sufficient schedule time must be included in the test program to allow these tests.

A useful practice before a potentially hazardous test is a peer review. The individuals planning the test should present their plans to a peer group not immediately associated with the test at hand. Then planners should discuss any hazards that have been identified and the procedures designed to minimize such hazards. The reviewers should search for unforeseen problems and consider the efficacy of the proposed procedures to minimize hazards. Further, the planners should present the "built-up" approach while the reviewers ensure that the approach is logical. The results of these reviews should be fully documented and no significant deviations allowed without further review.

4.12 Joint Reliability and Maintainability Evaluation Teams (JRMET)

A final planning effort should include establishment of a group to participate in classification of R&M data and review of results. The basic nature of R&M data drives the need for such a group.

In many respects, R&M data are more subjective than data from other engineering disciplines. Often, it is not clear that an anomaly is an inherent defect or was somehow induced. Similarly, there is often disagreement as to the criticality of failures. Further, contracts often contain definitions of failure that are significantly different than those normally used by the operating command.

The U.S. Air Force A-10 development contract defined a failure as a loss of mission critical function that occurred after the end of the preflight inspection and before the start of the postflight inspection. That very artificial definition excluded all noncritical failures and many failures not discovered in flight. The user's definition of failure included all maintenance actions needed to correct inherent defects. Both definitions were used to develop a MTBF. As a result, the weapons system advocates reported a MTBF over ten times higher than the more independent testers. This large discrepancy surfaced at an important program review and the chairing flag rank officers were notably displeased.

Adding more confusion is the often large difference between the flight test environment and the eventual usage environment. Considerable engineering judgment is needed to translate flight test results to expected fleet results.

Establishing a team is a way to obtain consensus and increase understanding of the somewhat subjective results. If agreement cannot be reached on all issues, at least points of disagreement can be isolated and order-of-magnitude disparities eliminated.

Acceptance of R&M results is maximized if all program participating agencies are represented on the JRMET (sometimes called a scoring conference). This

includes government program management, contractors, test agencies, independent oversight agencies, and support agencies (repair depots). If the government is providing a significant amount of equipment to be integrated into a vehicle, the supplying government agency should also be represented.

This group should be formed before test planning is complete in order that the test can be structured such that all participant's objectives can be met. The JRMETs can be formally chartered. Such a charter should list roles and responsibilities. An example charter is included in Appendix B.

Once flight testing begins, the group should meet periodically (perhaps monthly) to classify new data and review results. The details of the classification process are discussed in the following test conduct section. One way to conduct the data review is to provide all group members a computer listing of new (since the last review) R&M data for review prior to a formal meeting. The listing should be provided enough in advance that team members can get information needed for classification decisions. Particularly, the contractors must have sufficient time to provide preliminary failure analysis.

Some test programs are using computer networks to provide team members with ready access to R&M data. Team members use remote computer terminals to review data from their home office prior to the meeting. At meetings, computer screen data are projected in large enough scale for participants to conduct discussions and reach agreements.

5.0 TEST CONDUCT

5.1 Initial Inspection

When the first and subsequent aircraft are delivered to the test site, an exhaustive physical inspection should be conducted. The purpose of these inspections is twofold: to inventory or baseline the aircraft and to ensure the aircraft is truly flight worthy.

The aircraft inventory and baseline are conducted to find what equipment was delivered with the aircraft. In the early stages of aircraft programs, equipment shortages are common and the testers must understand how the aircraft is configured. The inventory begins with a careful review of all associated paperwork. The individual aircraft paperwork should list all deviations to the baseline design. If the manufacturer was authorized to not comply with any specific requirements, such waivers should also be listed in the aircraft paperwork. These deviations and waivers must be of sufficient detail to allow the test agency to conduct the inspections needed to ensure that flight safety is not degraded.

One U.S. Air Force aircraft type was delivered with the "blanket" waiver stating: "Certain clearances within the hydraulics and flight controls subsystems are not to military standards." This very general statement did not provide enough detail to allow the aircraft to be properly inspected for potential control systems binding or chafing. As a result, throughout the test program the aircraft was plagued by a host of minor chafing problems.

The using command did not get off so easy. As least one aircraft was lost in fleet service because of control system cable binding. To prevent further losses, special inspection procedures were set up, certain aircraft compartments were painted white to ease inspection and painfully rigorous foreign object damage processes were used. The best solution would have been to design in adequate clearance. When that was not possible, each potential interference point should have been carefully noted and inspections planned. The added up-front effort would have been cheaper than an aircraft.

When the paperwork is satisfactory, the aircraft should undergo a careful review to ensure that the hardware matches the "as-delivered" configuration information. This usually means removing all access/inspection panels and possibly large units such as engines. The part numbers and serial numbers of major line replaceable units should be recorded along with the hour-meter readings on those units. The hour readings will be needed to calculate time to failure measures for those units that fail. The part and serial numbers are essential to understanding the aircraft configuration as modifications are made to the units.

Along with inventorying equipment and recording data, the aircraft should be thoroughly inspected for design and workmanship errors. Test aircraft are normally produced on "soft" tooling with preliminary blueprints by technicians that are just beginning to learn the processes needed. The probability of error is very high. This inspection should be done by the most experienced maintenance technicians available. While

many defects can be found easily, good inspection equipment such as lights, mirrors and borescopes will increase the percentage of problems found. Modern fiber optic borescopes with self-contained illumination and remotely controlled steerable heads greatly improve access to restricted areas. Some current borescopes provide a video output for easy recording of inspection results.

If video recording is available, it is an economical medium for recording defects found. Still photography can also be used. Figure 7 shows an example of a wiring defect discovered during an initial inspection. Both cases show wiring chafing against aircraft structure. In the airborne vibration environment, insulation wear-through and eventual electrical shorts were inevitable. Besides those two, 37 other wiring/cabling defects where noted and corrected on that specific aircraft. Figure 8 is a somewhat different defect. An engine bay fire warning loop assembly is resting on aircraft structure. When vibration and chafing wears through the line the engine fire warning will activate, the pilot will declare an inflight emergency and use the fire extinguishing agent. After landing, the problem would be found, but the labor to clean up the extinguishing agent will delay the test program noticeably.

After the inspection and required fixes, it was felt that the aircraft was safe to fly. Before ten sorties were completed, the pilot declared an inflight emergency after many flight control failure indications. When the aircraft was dismantled, the evidence told a clear story; a wire bundle had chafed through and started an inflight fire in an area that had not been inspected.

Evidence of defects such as these must be fed back to the manufacturer to prevent recurrence. Aircrews usually have strong opinions on matters such as inflight fires and can be counted on to lend their voices to the efforts to convince the manufacturer to improve his product.

As noted, even the initial inspection offers an opportunity to develop improved maintenance practices. After the inflight fire, the initial inspection was considerably more rigorous. Also, the initial inspection is the first chance to note access problems.

5.2 Scheduled Maintenance/Servicing

Frequently performed tasks such as pre/postflight inspections often consume fifty percent of the maintenance labor hours on military aircraft. For reliable transport type vehicles, the figure is even higher. During the fleet life of these vehicles, frequent actions may be performed millions of times. Because of this high number, even the slightest labor and time savings can be important over the service life of the vehicle.

Early in the test program engineers and experienced maintenance personnel should carefully scrutinize these commonly occurring tasks. Videotape recordings can show where task flow might be improved and time saved. Desktop computers with process flow analysis software can also help. Portions of tasks that cause difficulty might be improved with more training or different tools. One recent analysis showed a noticeable improvement in task times when the maintenance technicians were simply provided a better quality flashlight to perform aircraft interior inspections.

Besides performing tasks in the optimal manner, the value of performing the particular task should be questioned. This is particularly true of inspections. Each step in any inspection should be carefully reviewed to establish a firm need for the task. Often the tendency is to inspect if there is any doubt as to the possible need. This over-inspection adds to downtime and labor costs. Sometimes, over-inspection may increase the probability of maintenance error and actually detract from the capability of the vehicle.

If an inspection or preventive maintenance task is needed, the task frequency should be limited to that essential to safe and economical operation. Often, the inspection interval for newly-designed aircraft is relatively short because of the many uncertainties with new vehicles. This is often prudent, but a plan should be developed to increase the intervals as data are gathered and uncertainties are eliminated. For example, it is good practice to perform Spectroscopic Oil Analysis on the fluids in new aircraft even if it is not specifically recommended by the manufacturer. This should be done before the first flight and after the first

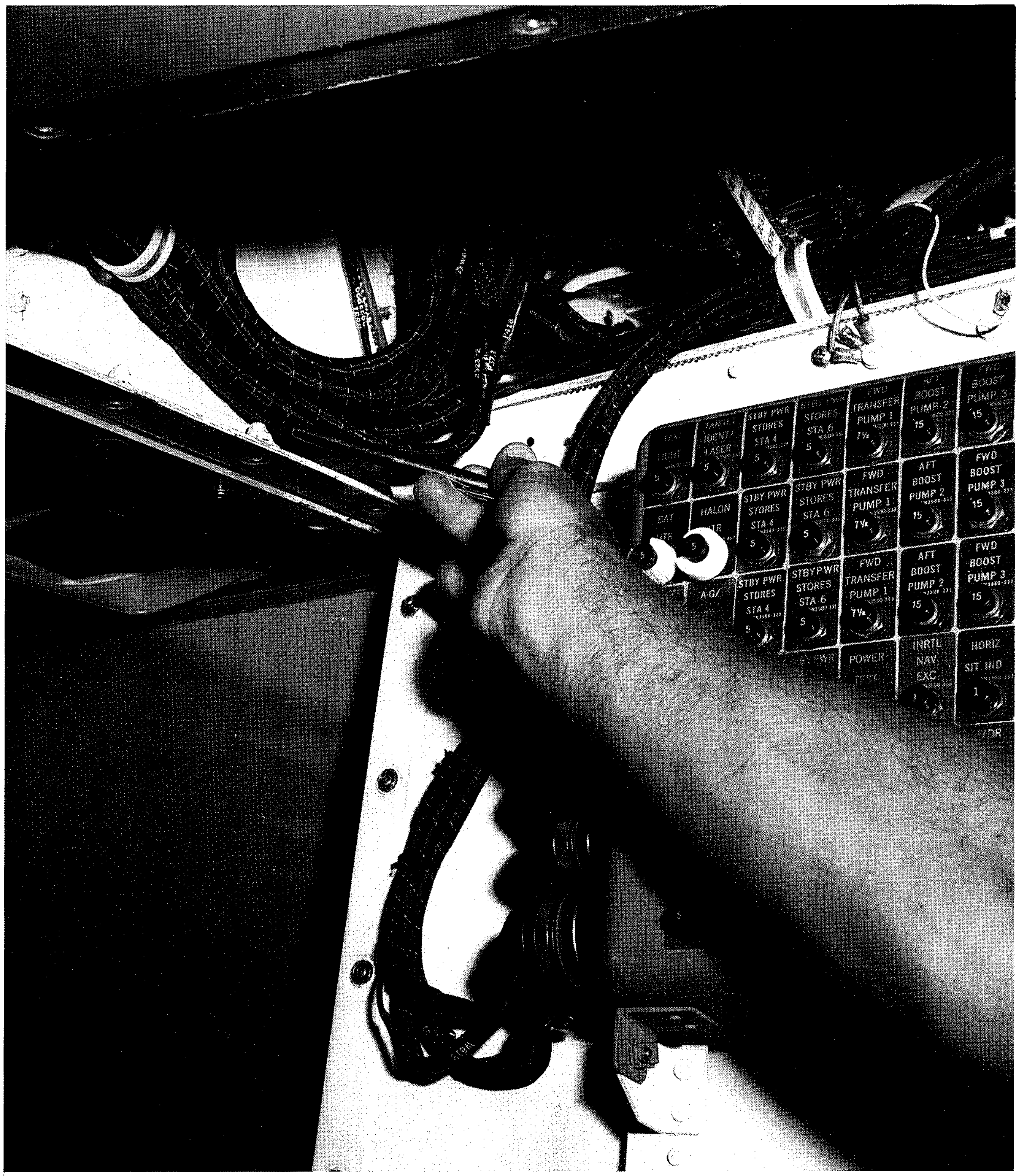

Figure 7 Wire Chafing Discovered During Initial Inspection

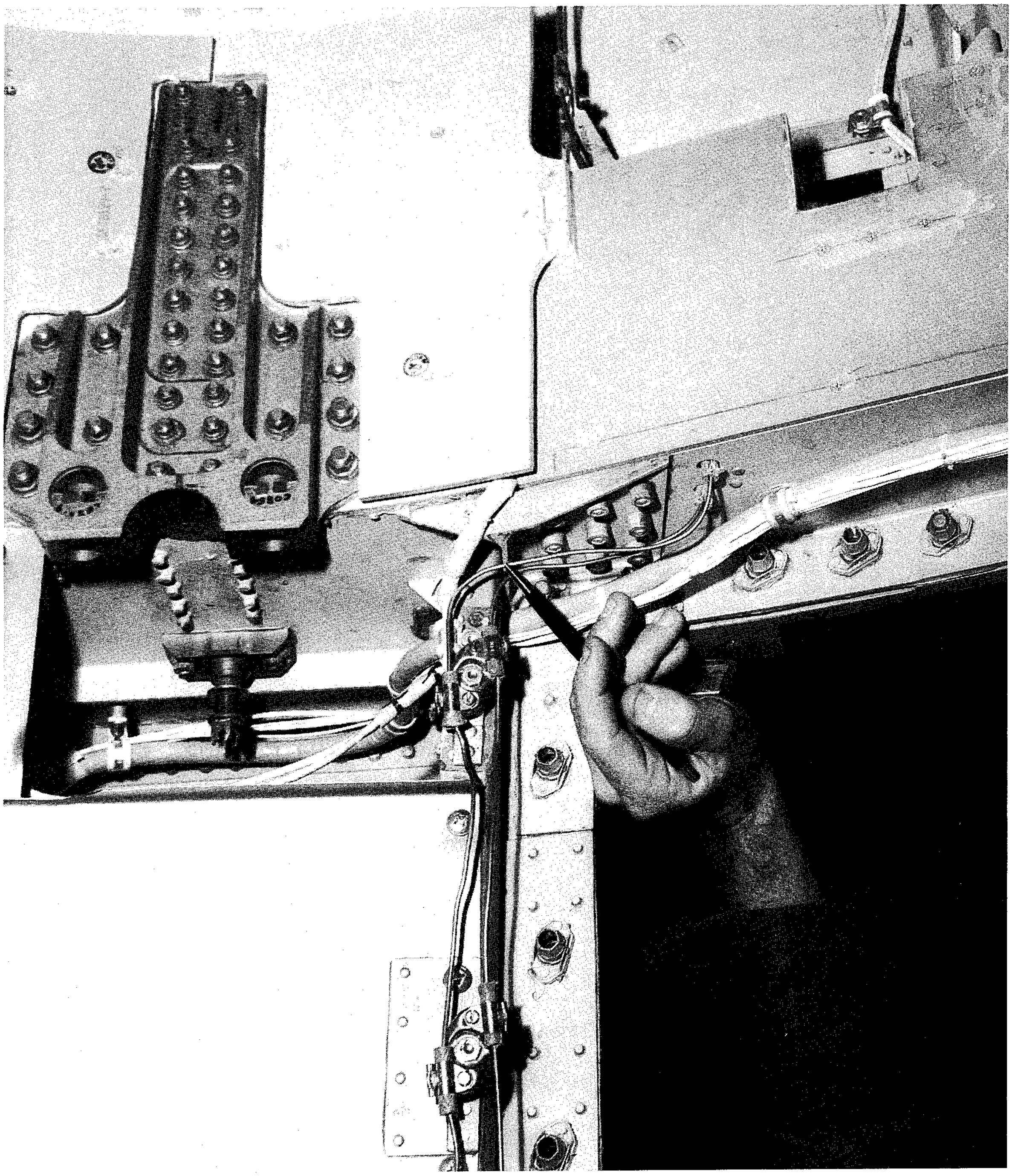

Figure 8 Fire Warning Loop Chafing Discovered During Initial Inspection

several flights. The fluid metallic content measurement provides a potential early warning of problems. But, once the metallic content is seen to be satisfactory, a maximum interval should be developed.

Once a scheduled maintenance task is considered optimally structured, a standardized time should be agreed to and predictions updated. The standardized time can then be used in simulations and models.

Scheduled maintenance tasks must also be considered in climatic extreme conditions. Under those conditions, times will likely increase significantly. Sometimes it will be necessary to change procedures to accomplish maintenance tasks. Those special procedures should also be optimized and technical data changed appropriately. Resulting times should also be standardized and used in appropriate models and simulations. In this manner, aircraft maintenance requirements in extreme conditions can be predicted. AGARDograph Volume 8, Series No. 300 also discusses flight testing under extreme climatic conditions.

5.3 Unscheduled Maintenance/Reliability

Unscheduled maintenance is that work required to fix failures (real or suspected). That work is the source of flight test reliability data and measures. During the test program thousands of failures may occur. Some will be more significant than others. If the program was properly planned and well implemented, the R&M engineers should not need to spend much time on the day-to-day data collection efforts. Instead, the test engineers should focus on classifying and analyzing results. With thousands of failures to consider, the engineers must have some order-of-battle to structure their efforts. The following discussion is not the only method of classifying R&M data, but has proven helpful on a number of programs.

An ideal reliability evaluation would analyze and fix every failure mode that occurs. Practical limitations like time and moneys always make that impossible. First, fix the problems that affect safety of flight. Then, those items that prevent mission completion must be corrected. Lastly, those noncritical failures that affect availability and cost should be addressed.

This order of precedence should guide engineers during the test program. For every failure that occurs, decide if there is any scenario where the failure would decrease safety. This is not as obvious as it looks. If the failure occurred during clear daytime flight, what would have been the impact if the problem arose during night or adverse weather conditions? What if this had been a second failure? For weapons delivery platforms, what if the failure had occurred during the stress of combat conditions? Aircrew experience is essential during these deliberations. The R&M test engineers must regularly consult with operations personnel to understand the significance of failures.

Do not neglect ground operations. Toxic materials, high pressure systems, and ordinance are a few of the hazards that have caused lethal accidents in the past. Every failure must be reviewed to consider the potential safety implications on ground operations.

If a failure does not affect safety, it may still be mission critical. For every failure, the astute R&M engineer must decide if the failure would prevent any of the aircraft's designed missions. Experienced aircrew must also be consulted in these determinations. Further, many flight occurrences lead an aircrew to believe a failure has occurred, but later investigation cannot find any failure. As much as 30 percent of aircrew reported avionic problems cannot be traced to a failed component. But, if the aircrew believes a failure has occurred, then the crew will act on that belief. That may include a mission deviation or, more seriously, a mission abort. If the crew does decide to continue the mission, they will likely quit using the suspect equipment and resort to a less capable alternative equipment. This means that a mission critical anomaly has occurred although no hardware failure exists. This situation must be treated in much the same way as a hard failure; i.e. the problem must be investigated and eliminated.

The least significant failure category is that class of defects that have no safety affect and do not prevent mission accomplishment, but still consume time and resources to correct. These problems can be considered in two broad, general classes: deferrable and nondeferrable. The nondeferrable problems are those that must be corrected before the aircraft can be dispatched on the next mission. Deferrable problems can be postponed until a scheduled maintenance period.

Obviously, those failures that prevent an aircraft launch must be fixed first. Deferrable problems must be considered in light of the total amount of time that

aircraft is unavailable for use. For example, simple maintenance tasks such as resealing panels become nontrivial when the sealant cure time is long (as much as 24 hours sometimes).

In summary, failures should be considered in four general classes: safety-critical, mission-critical, noncritical-nondeferrable and noncritical-deferrable. While safety-critical failure modes must be eliminated (and usually are), the less severe failure modes should be fixed if cost effective. Generally, not enough problems are fixed. That is, more front-end investment in reliability improvement would lower life cycle costs. History does not document a single instance of a military/aerospace product with excess reliability (measured in life cycle cost).

During program conduct each failure should be classified as to severity as discussed before. Also, each failure should be classified as to cause: i.e., inherent defect, induced defect or no defect. The latter class includes those cases where no actual failure is ever found. The computerized maintenance database should be capable of storing and recalling these classifications. The database should also be capable of recalling all data associated with these categories.

For databases with those abilities, a most useful computer product is a listing of the most common failing items in each category. With such a listing, it is easy to see where the engineering emphasis must be placed to improve the vehicle. The test R&M engineer should review this "high-burner" listing to insure that the most frequently failing items are being corrected. Similarly, lists of the items receiving the most induced failures and the most no-defect type failures must be reviewed to insure that all are being corrected.

As the test program progresses, the R&M engineer must search for the cause of failures and advocate any action needed to prevent recurrence of those failures. Once a particular part is deemed worthy of further investigation, the action to be taken depends on the tools available to the engineer. If flight test instrumentation is available to measure the environmental stresses (like temperature and vibration), a quick course of action may be to review existing data to insure that the equipment is not being damaged by the environment. If the environment proves benign or instrumentation is not available, a detailed failure analysis (much like an autopsy) may provide the cause of failure. If the failure analysis points to an environmental overstress it may be necessary to add instrumentation to measure the operating environment. This is a lengthy process, but needed if the problem is severe enough. If the failure cause is overstress, the needed fixes are also difficult. Either the failed part must be made more environmentally durable or the operating environment must be improved.

For heat related problems, sometimes cooling air allocations can be changed and more or cooler air supplied to the problem component. But, this lowers the cooling available to the rest of the system unless air conditioning subsystem modifications are made. If modifications are made to increase cooling capacity, then more energy (such as bleed air or electrical power) will be needed.

For vibration related problems, improved isolation or energy absorption devices may attenuate the failure inducing energy enough to improve reliability. Unfortunately, such devices consume space and add weight.

Fortunately, most (as much as 90 percent) failures can be prevented from recurring by eliminating internal design and manufacturing errors.

For those problems that are not considered inherent defects but, induced failures, the objective is the same: prevent recurrence. The most common causes of induced failures are aircraft operation outside design limits (pilot error), maintenance induced damage (maintenance error) and secondary failures. When errors occur, the normal reaction is to find the guilty and inflict sufficient punishment to insure more care in the future.

But, this approach only insures that the currently guilty do not repeat the offense. Prevention of future errors requires a proactive action. Anytime a pilot or maintainer commits an error, the flight test engineers must search for the underlying reason. Potential reasons for human error include unfriendly hardware design, trap-ridden software, etc. Many errors have more than one factor. Review of aircraft accident reports shows the spectrum of things that can lead to human error and should be mandatory reading for the novice flight tester.

An oft-advanced fix for human error is to improve the training given. Often this is the only cost effective way

to eliminate problems once an aircraft is in fleet usage. During flight test it may be possible to change the design to remove the source of potential error and this option should always be considered first.

In some cases, tasks are so difficult that the probability of error is significant even if utmost caution is used. In some early versions of the F-16 aircraft there was a requirement to tighten a steel oil line to a steel fitting at a torque of over 100 foot-pounds. That torque figure was appropriate for the steel fittings used. The steel fitting however, was threaded into a magnesium gearcase. The technical instructions carefully specified how wrenches were to be used. But access to and visibility of the area was almost nonexistent. As a result, when tightening the steel line, the maintainers would accidentally transfer the 100 foot-pounds of torque into the magnesium gearcase. On the ground, the stripped threads were not apparent. In flight the engine vibration quickly loosened the stripped fitting, the oil drained overboard, and the aircraft generator froze. Usually the emergency power unit functioned properly and the pilot landed the vehicle. After ten such instances, the design was changed to prevent such accidental overtorquing. Here, the safety of flight issue made an error-proof design essential and the hardware was modified.

Not all induced failures are the result of human error. Secondary failures are those failures that occur when associated equipment fails and induces other failures. Sometimes, the original, or primary failure, may be insignificant compared to the resulting secondary failure. Consider the case where a small forward-mounted fastener loosens and departs the aircraft--through the engine. Here the primary problem (the lost fastener) was induced by human error (insufficient torque) and the secondary failure was catastrophic.

In another memorable case, a thyratron (high power switching device) failed and killed eight other electronic components. The thyratron was inexpensive (U.S. $200) and had a low expected reliability of about 1,000 hours mean life. One of the secondary failures was an expensive pulse forming network that should have been ailure-free. The design was changed to prevent secondary failures.

In summary, all induced failures, whether caused by human error or system design, must be investigated for cause and a reasoned decision made to alleviate the problem.

The last class of problem is considered the no-defect failure. This seemingly paradoxical situation arises when the aircrew or the built-in-test reports a problem and maintenance cannot cause the problem to repeat or find any failed components. The situation where the aircrew reports a problem and maintenance finds no defect, but the symptoms repeat until a problem is eventually found is not within this no-defect class. Instead, this is a maintainability problem. This no-defect anomaly arises more often than normally expected. Experience shows that about 30 percent of all reported avionic faults result in no failed component being found. On some aircraft, the no-defect rate is considerably higher.

In the expert's opinion, most intermittent avionic faults are caused by defective connections in electrical connectors. This is a particularly insidious failure mode to find. When the electrical connector is demated for troubleshooting or inspection, the problem normally vanishes. In fact, any movement of the electrical cabling or connector may be sufficient to improve the connection enough to restore the system to operation. This problem exists with all electronic systems, but is particularly acute with aircraft because size and weight considerations lead to the smallest possible connectors. Gold-plated contact surfaces are used to maximize conductivity and minimize oxidation, but connectors remain a problem.

The best way to minimize connector problems is to minimize connectors (not surprising). The F-4 series aircraft had 905 electrical connectors while the more recently designed F-18 (by most measures, the most reliable U.S. fighter) has 808 connectors. The significant decrease in connector count, combined with the increased avionic capability of the F-18, shows that careful design can help. The flight test community must always search for ways to simplify aircraft--connectors included. Flight test must also carefully scrutinize cabling, connectors, and supports for mechanical integrity. Vibration prone cabling/connectors are failure prone connectors.

5.4 Unscheduled Maintenance/Maintainability

The maintainability analysis methods used for scheduled maintenance also work for unscheduled

maintenance. An important difference between the two categories of maintenance is troubleshooting. The more complex the system, the harder the fault isolation process. Electronic systems with more than one LRU "black box" often require more time to fault isolate than to physically repair. Even the most experienced technicians cannot isolate the failed LRU in some older aircraft systems. When that occurs, all suspected LRUs must be replaced (sometimes called shotgun maintenance). The cost of this inefficiency make it imperative that R&M engineers fix such problems. Many aircraft contracts require a fault isolation capability that will isolate any failure to a single LRU. The isolation capability may consist of troubleshooting instructions (technical data), ground test equipment, built-in-test, or any combination. During the test program, any failure that cannot be isolated must be studied in detail. The R&M engineers must report the failure mode, fault isolation problems and recommend the changes needed to improve the isolation process.

5.5 Contractual Requirements Verification

An important (and very visible) element of the flight test is verifying that the contractor(s) achieved the R&M levels specified in contracts. The process is made more difficult by the wide variety of R&M measures used in different contracts. Further, every contract seems to reinvent circumstances which must be excluded from consideration. Generally, the purpose is to assign liability for all occurrences caused by the contractor's design and manufacturing efforts. Conversely, liability is withheld for occurrences beyond the contractor's control. The concept is simple in theory and difficult in practice.

For example, maintenance technician error is beyond the control of the contractor and excluded from consideration. However, if the error was induced because the technician followed incorrect instructions in contractor-provided technical data, the occurrence must be considered. An even more subtle problem occurs when the contract specifies a journeymen-level technician must be able to perform all maintenance tasks. Then, when maintenance error occurs, there is an inevitable dispute over whether the task is to difficult for a journeymen technician. Contracts seldom discuss such subtle nuances which must be negotiated with the contractor. The JRMET or equivalent group is an excellent forum for such negotiations. The results must be carefully documented throughout the test program.

During the test program every occurrence must be assessed for chargability against reliability and maintainability guarantees. That is, all reported defects and maintenance actions must be reviewed to determine if they are attributable to the contractor's design or manufacturing processes. Again, the JRMET or it's analog is the correct forum for such classification. Once a decision has been made, each action should be tagged as to the contractual relevance. This tagging or classification should be entered into the computer database.

5.6 Built-in-Test

Built-in-test (BIT) is a widespread technique used to help in fault isolation. This self diagnosis capability is also used to aid aircrews by showing that critical equipment is working. Aircraft contracts often state something like: "Built-in-test shall detect 100 percent of all mission critical failures and isolate 90 percent of all detected failures to a single LRU." False alarms (incorrect indication of failure) are always a problem and contracts normally specify a maximum false alarm rate. Final development and assessment of the BIT capability is an important part of the R&M test effort.

All reported failure indications and maintenance actions must be assessed as to the success, failure or nonapplicability of BIT in each instance. Once again, this is a JRMET task. The results of the assessment should be entered into the computer database. When the database is complete, calculation of BIT measures of merit is straightforward.

5.7 Summary

Much of the practicing R&M engineer's time is spend classifying reported failures and maintenance occurrences. Reported failures must be classified as to : safety criticality, mission criticality, cause, and BIT effectiveness. Also, contractor attributability must be determined. Once the classification process is complete and the computer database is updated, calculating R&M measures of merit is easy.

6.0 DATA ANALYSIS AND PRESENTATION

Besides data classification, data analysis is an ongoing activity throughout the test program. The previous chapter briefly discussed the "high-burner" lists of most frequently failing parts and emphasized the need

to find and fix problems. This improvement process is the real "value-added" of a good R&M test program and all data analysis should support that objective.

6.1 Production Readiness

After finding and fixing problems, determination of production readiness is the highest payback effort. An important program milestone is the beginning of production. It is certainly the most politically visible. Production startup means committing large amounts of money to the program and is almost an irreversible commitment to the system. The flight test results are often scrutinized and criticized in the technical and political arenas. The political champions of the weapons system will loudly broadcast positive flight test results and downplay any negative results. The weapons system opponents will seize any shortcoming discovered during test and herald it as evidence of developer incompetence. If there is no negative news, the opponents will likely question the test data and in extreme cases, question the integrity of the testers.

The production readiness question is particularly difficult for the Reliability and Maintainability engineers because of the reliability growth phenomena. If the R&M engineers have been successful, the system reliability has steadily improved during the test program. More over, many problems that were discovered during test could likely not be economically fixed on the test vehicles, but could readily be fixed in the production versions of the aircraft. The challenge is to predict the reliability and maintainability of the production aircraft using data from test versions of the vehicle. This must be done rigorously to fend off the inevitable criticism from those disappointed in the results.

One method is shown graphically in Figure 9. That method of plotting reliability growth on log-log scales is called the Duane reliability growth model (Reference 1). This illustration first plots the reliability growth during the F-20 test program. The first portion of the plot, between 100 and 645 cumulative flight hours, shows the actual reliability measured during flight test. Figure 9 shows the measured cumulative reliability as 1.9 hours meantime between maintenance(inherent) at the 645 flight hour points. Also shown is the measured reliability growth rate (alpha) of 0.25. The area of the plot between 645 and 10,000 flight hours is a projection based upon the measured 0.25-growth rate. The 0.25-growth rate is conservative and generally considered low- risk.

More controversial is the step improvement shown at the 645 flight hour point. That step represents the improvement expected from programmed changes. Table 11 lists the changes planned. The cross-hatched area in Figure 9 represents the uncertainty in estimating the reliability improvement. This type of presentation is a method to project future reliability from current test results. The obvious weakness' of estimating the reliability of improvements and assuming a growth rate can and are criticized. The advantage is that these assumptions are visible and can be discussed and justified in detail. Commonly the improvements are obviously low risk. For example, Table 11 lists radial tires as an improvement. The reliability improvement of radial over bias ply tires is well established and that particular change should not be questioned. Other changes, such as the digital displays, are harder to estimate and justify a reliability improvement. If the improvement is a completely new development, the initial reliability may be lower than the proceeder item. Then it is necessary to plan a reliability growth for the "improved" item.

Table 11
F-20 Planned Reliability Improvements

• Digital Displays
• 40 KVA Generator
• Main Battery
• Fuel Quantity Indicator
• Radial Tires
• Display Processor
• Inertial Navigation Unit
• Tail Beacon
• Windshield Sealant

Similarly, maintainability must be predicted from flight test data. Where major changes, such as shown in Table 12, are planned, a growth plot and step improvement is appropriate.

The preceding assumes that the system is ready for production or at least close. The situation is much more difficult if it is not ready for production. The onus is usually on the testers to clearly prove that the system is not suitable for production and what changes are needed. Recent U.S. programs such as low-altitude navigation and targeting infrared for night (LANTIRN)

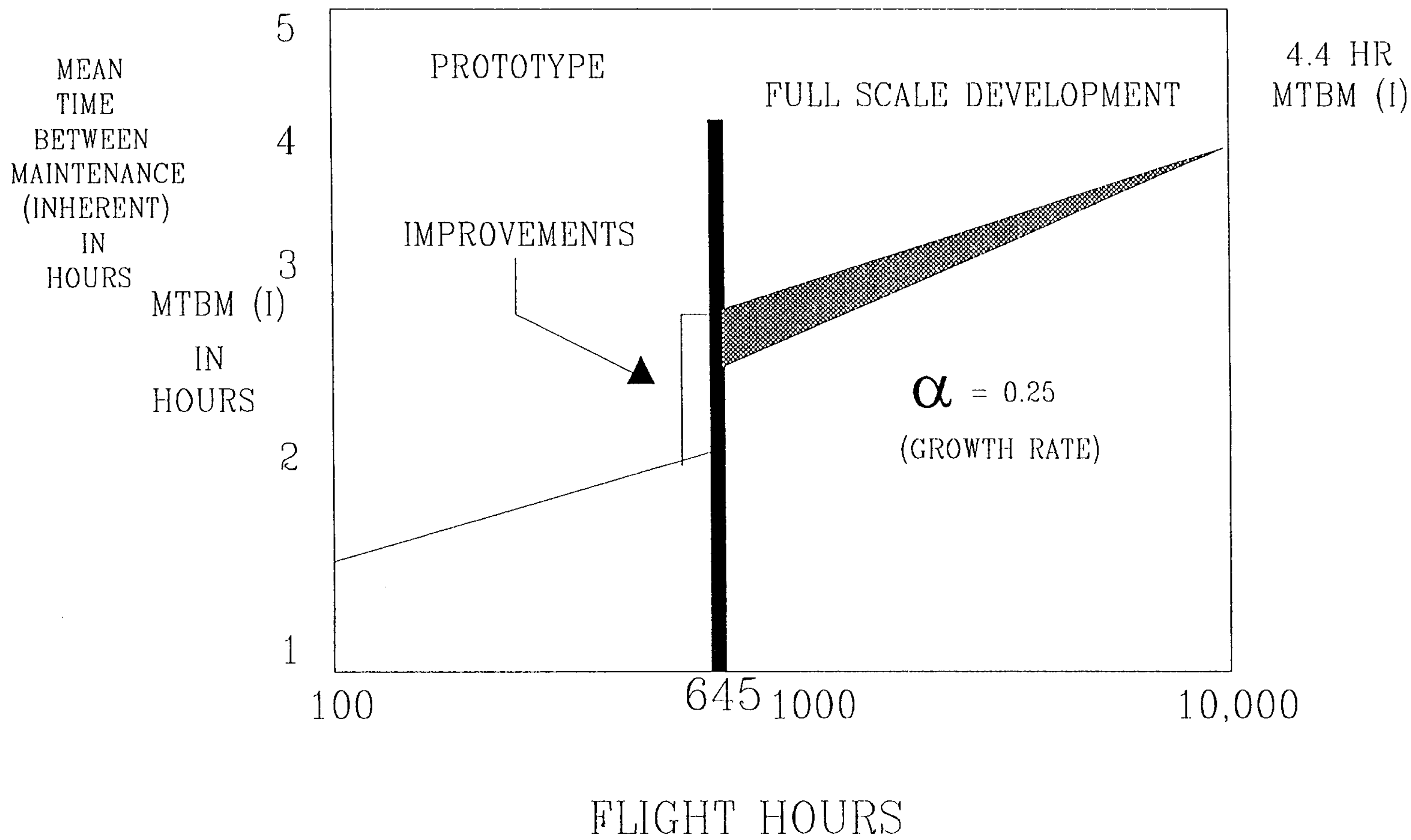

Figure 9 F-20 Reliability Growth

and the advanced medium-range air-to-air missile (AMRAAM) have suffered production delays until reliability has been improved and demonstrated. In these cases, the political arena became interested and the onus was on the developer to prove reliability was sufficient.

Table 12
F-20 Planned Maintainability Improvements

• Onboard Oxygen Generation System
• Engine
- ignitor box
- support equipment
• Airframe
- hinge radome
- bleed air duct
- radar air dehydrator

6.2 Specification Verification

Demonstrating manufacturer compliance with contracts and specifications is one of the more contentious aspects of flight test R&M evaluations. The manufacturer is strongly motivated to demonstrate that the aircraft meets all R&M requirements. If the testers claim otherwise, they had best have complete evidence to show any noncompliance. The first area questioned will likely be data collection accuracy. Once the testers prove that the data are accurate, the data interpretation will be scrutinized. This means that the data analysis must be rigorous to withstand challenge. Often, specifications are both qualitative and quantitative for R&M.

Qualitative reliability is usually easy to verify or disprove. A single occurrence of a proscribed action will show noncompliance. Some qualitative reliability requirements can be verified by inspection of the design and aircraft. These requirements often take the form of specifying certain functional characteristics such as: "All electrical connectors shall provide protection from any anticipated environment." Inspection will show if environmental connectors are installed. The problem becomes more difficult if an environmental connector fails to provide adequate protection. A photograph would demonstrate that the connector did not provide protection, but some evidence of the environment at time of failure is also needed. Obviously, a connector might be designed to withstand a certain humidity level, but would not function long if submerged.

Other qualitative reliability requirements are not as readily demonstrable. A common flight controls system requirement is: "No single-point failure shall cause the probability of aircraft loss to exceed one part in a million." A careful review of the design will help verify that the requirement has been met, but it is possible to overlook subtle details. As flight test proceeds, the subtleties should become evident. In one classic case, a quad-redundant flight control system had four power rectifiers using a common ground wire. Fortunately, the situation was discovered before the wire failed.

Qualitative maintainability requirements are also amenable to inspection. These requirements are designed to ease maintenance and to prevent maintenance error. Some common requirements are:

1. Captive fasteners shall be used for nonstructural access covers.

2. Keyed electrical connectors shall preclude mating to wrong receptacles.

3. No adjustment, other than operator controls, shall be required when replacing one or more units.

There are many more common qualitative requirements; the testers should develop a checklist to ensure all requirements are considered as the program progresses.

Considerable care is required to verify quantitative reliability requirements. The simplest and most common measure of reliability is MTBF. Both time and failure must be carefully and precisely defined. As discussed previously, time (or measurement of stress) is commonly defined as flight time. The flight test environment complicates the issue. For many reasons, flight test aircraft are likely to be operated on the ground more than a fleet service aircraft would be. This "excess ground operating time" adds stress to many aircraft components. If the aircraft ground cooling capability is not as good as the inflight cooling, it is possible that the ground environment is more stressful then flight. Provision must be made to account for the "excess ground operating time." The simplest way is to simply censor, or exclude failures that are obviously

caused by ground operation. Another method is to consider a ground operating hour as equivalent(in stress) to some fraction of a flight hour. Then, an "equivalent flight hour" can be calculated and used as a total measure of stress:

Equivalent Flight Hours = Flight Hours + "Excess Ground Hours" / Adjustment Factor

The environmental stress factors on U.S. Mil-Handbook 217 are commonly used for the adjustment factor in the previous equation. The handbook lists 6.0 as the ratio of stress difference between the airborne uninhabited environment and the ground fixed environment. This translates as saying that flight is 6.0 times as stressful as ground operation. Once equivalent flight hours are calculated, that figure can be used as the numerator in the various "Meantime Between" equations.

Failures must also be precisely defined. The earlier data classification section discussed the different types of failures and failure criticality. Specifications must clearly state what is considered a failure for any requirement.

A last factor causing difficulty in assessing quantitative reliability is the reliability growth phenomena. It is well established that reliability will improve throughout the development program if an effort is made to correct and prevent recurrence of failure modes. If reliability is improving as a function of test time, at what point should reliability be measured? The reliability shown at the end of test will be the most representative of that experienced in fleet service. But, should the cumulative reliability to date be used or perhaps a point estimate at the end of the test program? Should improvements planned but not implemented be included to estimate reliability?

Answers to these questions as well as definitions of stress time and failure must be fully addressed before attempting to assess specification compliance. Ideally, the flight test agency and the contractor would agree to all definitions before the start of test.

7.0 REPORTING

7.1 General

The most exhaustive test would have no value if the results are not used. The first step to usage is to make the results known. This chapter discusses some ways to report test results.

7.2 Deficiencies

All deficiencies must be reported when possible. The long lead times needed to implement changes make it crucial that defects be reported in a timely manner and corrective actions begun as soon as possible. Flight safety is also a major reason to spread the word about problems. If a deficiency has any safety-of-flight impact, the information must be disseminated immediately. Aviation history lists many cases where aircraft accidents would have been prevented if the right people had the needed information.

Many organizations have developed administrative systems to manage these technical problems. These systems consist of a form to capture all needed information and, perhaps, a computerized database to store the information. If possible, a computerized system is most highly recommended. Lengthy test programs on complex aircraft produce hundreds and sometimes thousands of deficiency reports.

Figure 10 is an example form completed to show the details of an aircraft reliability problem. Table 13 lists and explains the data elements on the form. As shown, the deficiency report focus is on a single narrow problem. Another important point to note is the level of detail. The information must be sufficient to convince readers that a problem truly exists and that the problem impact is sufficient to warrant a corrective action. Often the aircraft advocates and contractors are not pleased when told of problems with their prize creation and the flight test engineer must present a convincing argument. Analogous to a barrister arguing a case, the engineer must present compelling evidence to prove the existence and impact of deficiencies.

Any computerized data system should also track actions after the deficiency is initially reported. Some important information includes details of corrections and implementation effectively. Also, any additional flight test efforts needed to either better define the problem or to show the effectiveness of fixes should be included.

These deficiency reports should be considered action documents. This means the time between discovery of the problem and the report should be a matter of days (hours if flight safety is affected). Every report should

SERVICE REPORT RECORD

SUBJECT ☐ Category I Service Report ☒ Category II Service Report ☐ Repeat Category I/II Service Report ☐ Initial Acceptance Inspection	☐ Yes ☒ No Source Selection Sensitive (Protect I.A.W. AFR 70-15) ☒ Mission Essential Deficiency ☐ Degrades Mission Deficiency ☐ Proposed Enhancement

TITLE:

Excessive Failure Rate of Armament Control Panel (A-6 Card)

1. FROM 452 FLTS/EN	2. TO ASC/ENR
3. REPORT CONTROL NO. F-15CTF-94-001	13. OPERATING TIME AT FAILURE ☐ UNK ☐ N/A Various
4. DATE DISCOVERED 18 Jan 1993	14. GOVT. FURNISHED PROPERTY ☐ YES ☐ NO ☐ UNK ☐ N/A
5. NSN/FSN ☐ UNK ☐ N/A 5870-00-341-4221	15. QUANTITY RECEIVED | INSPECTED | DEFICIENT ☐ UNK ☐ N/A
6. NOMENCLATURE Armament COntrol Panel	
7. MFR, SHIPPER, OVERHAUL ☐ UNK ☐ N/A Polymorphic Systems	16. DEFICIENT ITEM WORKS ON OR WITH END ITEM | NEXT HIGHER ASSEMBLY
8. MANUFACTURER'S PART NO. ☐ UNK ☐ N/A C-935869-09	
9. SERIAL, LOT, OR BATCH NO. ☐ UNK ☐ N/A Various	17. DOLLAR VALUE ☐ UNK ☐ N/A
10. CONTRACT, PURCHASE ORD, DOC NO. ☐ UNK ☐ N/A Various	18. ESTIMATED CORRECTION COST ☐ UNK ☐ N/A
11. ITEM ☐ UNK ☐ N/A ☒ NEW ☐ OVERHAULED	19. ITEM UNDER WARRANTY ☐ YES ☐ NO ☐ UNK ☐ N/A
12. DATE MFD, REPAIRED OR OVERHAULED ☐ UNK ☐ N/A Various	20. WUC OR PSEUDO WUC ☐ UNK ☐ N/A 75QED

21. ACTION OR DISPOSITION ☒ HOLDING EXHIBIT ____WDS. | ☐ RELEASED TO | ☐ RETURNED TO | ☐ REPAIRED

22. DETAILS (CONTINUE ON REVERSE)

The Armament Control Panel has failed six times during the flight test program (140 hours, MTBF= 27 hours). In all cases the Master Jettison circuuit card assembly (A-6) had failed. Replacement of that card restored the failed control panels tp operation. Physical examination of the failed A-6 cards revealed no obvious cause. The conformal coating was intact and in good condition.

A. SUBJECT AREA	B. IMPACTS ON	C. HAZARD CODE (MIL-STD-882A)
Reliability	Operational Effectiveness Life Cycle Cost	☐ I ☐ II ☐ III ☐ IV

D. RECOMMENDATIONS (CONTINUE ON REVERSE)

A detailed physics-of-failure analysis required to determine the exact failurecause. The last two failed A-6 cards are being held by the test team. Recommend that these cards be returned to the manfacturer (or an independant test laboratory) for detailed analysis.

E. STANDARD REPORT DESIGNATOR		F. COMMAND CODE	
G. ORIGINATOR NAME & PHONE NO.	DATE	H. RELEASER AUTHORITY NAME, PHONE	DATE

AFTO FORM 240 JAN 79 PREVIOUS EDITION IS OBSOLETE

Figure 10 AFTO Form 240

Table 13
Deficiency Report Contents

Block No.	Block Title	Block Contents
none	Subject	Identifies type of report and lists the mission criticality.
none	Title	One sentence narrative describing the deficiency.
1.	From	Name and address of agency reporting the deficiency.
2.	To	Name and address of agency responsible for correcting the deficiency.
3.	Report Control No.	Number assigned for administrative tracking and control purposes.
4.	Date Discovered	Calendar date the deficiency was found.
5.	NSN/FSN	Part number unique to US military.
6.	Nomenclature	Name of the deficient part.
7.	MFR, SHIPPER OVERHAUL	Agency responsible for manufacturer, repair or transportation (if damaged in transit) of deficient part.
8.	MANUFACTURER PART NO.	Unique number assigned by the manufacturer.
9.	SERIAL,LOT BATCH NO.	Number to help identify deficient part.
10.	CONTRACT, PURCHASE ORDER	Number assigned to deficient part purchase paperwork.
11.	ITEM	Indicates if deficient part was new or overhauled.
12.	DATE MFD. REPAIRED OR OVERHAULED	Shows date deficient item was last renewed.
13.	OPERATING TIME AT FAILURE.	Measure of accumulated stress at failure.
14.	GOVT FURNISHED PROPERTY	Shows if deficient item was government provided.
15.	QUANTITY	Lists number of similiar parts available and numb deficient.
16.	DEFICIENT ITEM WORKS ON/WITH	Lists type aircraft and next level of assembly above deficient part.
17.	DOLLAR VALUE	Cost of deficient part.
18.	ESTIMATED CORRECTION COST	Self-explanatory.
19.	ITEM UNDER	Used to process warranty claims.
20.	WUC OR PSEUDO WUC	Hardware identifer code used in addition to part numbers.
21.	ACTION OR DISPOSITION	Shows what was done with deficient part.
22.	DETAILS	Most important entry on form. A narrative of pr lem and impact. Must hav enough information to al correction to be designe
A.	SUBJECT AREA	Lists area of deficiency (Design, Logistics, etc.
B.	IMPACTS ON	Lists technical area impacted by deficiency (R& Utility, etc.).
C.	HAZARD CODE	Shows safety impact of deficiency.
D.	RECOMMENDATIONS	Narrative decribing any potential remedy for the deficiency.
E&F.	--------	Military designators un to US Air Force.
G&H	--------	Identity of person repo ing deficiency.

cause a conscious decision made to either fix the problem in some manner or to live with it. If the problem cannot be fixed, the information should not be discarded. Instead, all such information should be carefully archived. Every aircraft is modified during its service life and it may be possible to fix the problems then.

7.3 Progress Reports

Several progress or interim reports are usually needed during the test program. These are often coincident with different program milestones such as production decisions. Customer needs should establish the contents of these reports. To the extent possible, these reports should be considered during the program planning phase. Report times and content should be planned.

Specifically, for production decisions, the program advocates will need to show how well the aircraft is doing in relation to contractual and user requirements. These program advocacy milestones may take the form of briefings to decision makers or summary level issue papers. In either case, limited time and space mean only the important issues can be discussed. For example, for production decision briefings, R&M is seldom allocated more than two briefing slides. As discussed earlier, reliability and maintainability growth curves will usually be needed to show that the vehicle is making satisfactory progress towards requirements.

Also recommended is a list of deficiencies discovered and the planned corrections. This list can be rank ordered with the most serious first. Such a list can convince various parties that the problems are being fixed. Often, the problems are reported in the news media, but the fixes seldom are. This type of candor establishes the credibility of the testers while correcting popular misconceptions.

7.4 Final Technical Reports

Traditionally, a final report is written at the conclusion of the program. These reports are not normally action documents. By the end of the test program, production is well underway and the time to make improvements is past. The final report should, however, summarize the test program including problems encountered and corrected. The report should also present a complete list of R&M parameters measured and current at the end of the flight test program. This includes growth projections as discussed earlier. Table 14 is an outline of one-way a final R&M report might be structured.

7.5 Lessons Learned

Some organizations have a formal repository of so-called lessons learned. These "lessons" are intended to document problems so that others may avoid unpleasant relearning experiences. Suitable lessons learned subjects may come from any phase of the flight test effort: planning, provisioning, execution or analysis/reporting. Also, any portion of the aircraft or associated equipment may provide a lesson that designers should learn from.

An excellent example of a programmatic lesson learned and ever relearned is the need for good failure analysis. History does not offer one instance of overanalyzing failures. To the contrary, too many failures are written off as "random" and needed improvements left undone.

7.6 Technical Society Papers

Many technical societies exist for every engineering discipline, R&M included. Often these societies publish journals and hold technical symposia. These are excellent opportunities for the individual engineer (or small team) to get publication credit and spread the word on important technical work. Many society publications are saturated with papers from academia and practical papers are often welcomed.

8.0 FOLLOW-UP

When the reports are written, the aircraft delivered to the customer and the test team scattered to the four winds, there is still more to do. The effectiveness of the R&M evaluation can only be measured by examining the user's success in operating the system. The more problems the user has, the less effective the flight test program was.

8.1 Accident Reports

Test agencies should routinely examine accident reports concerning systems they tested and others. When an accident occurs, the testers must ask themselves if they could have done anything that would have prevented that particular occurrence. Even if they where not the responsible test agency, there are lessons

Table 14
Reliability and Maintainability Report Outline

PREFACE: Relation of this report to other reports and work in progress

EXECUTIVE SUMMARY: A summary of the report with a brief description of the results, conclusions and recommendations

TABLE of CONTENTS:

LIST of ILLUSTRATIONS: Including growth charts, task timelines and photographs/drawings to illustrate problems

LIST of TABLES: Including R&M measures of merit

INTRODUCTION:

Background: Historical information such as preceding tests, program authorizations and direction

General: Test dates, hours flown, planned versus actual tests and critical issues and questions

Test Objectives: Focus of tests

Test Limitations: Any limitations which prevented complete accomplishment of test objectives

Test Item Description: Brief description of the article tested-- Differences between the test article and planned production vehicle should be carefully listed-- If a description is overly long and might distract from the focus of the report, an appendix might be used to describe the article

TEST and EVALUATION:

Test Methods: Including brief data collection, processing and analysis overview -- refer to appendix for detailed description

Test Results:

Overall Aircraft Results:

Individual subsystem Results:

Both aircraft level and subsystem results should include R&M measures, descriptions of deficiencies (refer to previous deficiency reports), and needed illustrations such as growth plots, task timelines and photographs/drawings to show problems, include confidence levels as appropriate, draw conclusions and make recommendations as appropriate and discuss needed changes and any further testing required.

CONCLUSIONS and RECOMMENDATIONS: A summary of important conclusions and recommendations in the body of the report

REFERENCES: Include sources for specifications, requirements, designs, and other helpful reports or documents

APPENDICES: Include(as needed) detailed descriptions of test methods, test articles and results/data, Sortie or Missions Summaries, Deficiency Reports

to be learned from every accident. The reports contain a wealth of detail that can help improve and justify future test efforts.

8.2 In-Service R&M Data

Test Agencies should also examine the in-service R&M results from the aircraft that they and others tested. Comparisons of actual usage with test program results will quickly point out any weakness with the test process and allow better tests in the future. This is particularly important when test results are used to extrapolate to predict mature system R&M performance. As discussed earlier, the test program should significantly improve the R&M of the aircraft. If further improvement is expected in the production version of the aircraft, such expected improvement should be verified by analysis of in-service data.

Sometimes test agencies must review in- service R&M data as a protective measure. If the fleet R&M results are significantly less than measured during the test program, the tester's credibility is questioned. During the F-15A acquisition program the aircraft central computer was specified to have a 2,000-hour MTBF and measured 1,846-hour MTBF during flight test. After the production aircraft were delivered, the in-service results showed a 44-hour MTBF for the computer. The drastic difference and the high computer cost quickly got the attention of many flag rank officers and the testers were questioned. When the flight test results were easily defended, the question shifted to ask why in-service results where so bad. After a detailed analysis, the answer was apparent. The software was still evolving and the computers were often removed for reprogramming. The in-service R&M data collection system considered any removal, regardless of cause, as a failure unless it was specifically told that no failure existed. All removals were traced, by computer serial number, through all levels of repair and only those computers requiring physical repair were classed as failures. After that exhaustive reconciliation effort, the MTBF was recalculated as 1,780 hours for in-service use. The flag rank officers were mollified. The testers gloated and gleefully pointed to the in-service data collection system as yet another example of user incompetence.

8.3 Modification Requirements.

Another measure of the development program success is the need for modifications after the aircraft has been delivered to the user. The testers should monitor the modifications needed to see if problems went unnoticed during the test program. Academician G. V. Novozhilov, writing in the U.S.S.R. publication VESTNIK, discussed reliability of wide-body aircraft. As part of his work, he compared the complexity and reliability of the II-62 and II-86 flight control systems. Quoting: "One can judge the complexity of the control system of a modern aircraft by the number of units that make it up. Thus, for the II-62 aircraft control system there are some 16 units, 78 for the II-86." Academician Novozhilov continues to discuss the technique used to develop reliable flight controls for the II-86. He summarizes by comparing the modifications needed in the first 4 years of II-62 service with the first 4 years of II-86 service. Figure 11 reproduces that comparison and clearly shows the improvement.

9.0 FUTURE CONSIDERATIONS

The easing of global tensions will mean a continuing decline in funding for military purposes. This alone would translate to an increasing demand for reliable and maintainable equipment. Coupled with the emerging processes and technologies, the time is right for a drastic increase in R&M performance.

9.1 Processes

In the past, too much emphasis has been placed on measuring R&M and not enough on designing reliable and maintainable equipment. This realization, along with improved computer design tools, is leading to a shift in emphasis. A fundamental way to improve reliability is to design equipment with sufficient integrity to thrive in the intended environment. New thermal and vibration computer analysis tools are increasing the ability of the designer to test the design before metal is cut. Anthropometric computer simulations are being used to test the man- machine interface. This will eliminate many maintainability difficulties before any fabrication begins.

9.2 Technologies

Reliable, accurate navigation systems have been a major aerospace problem for decades. With the deployment of the global positioning system and the development of ring laser gyros, the solution is near. Systems with 5,000-hour MTBF are feasible. The price and size of these systems will allow dual redundancy for essentially infinite mission reliability.

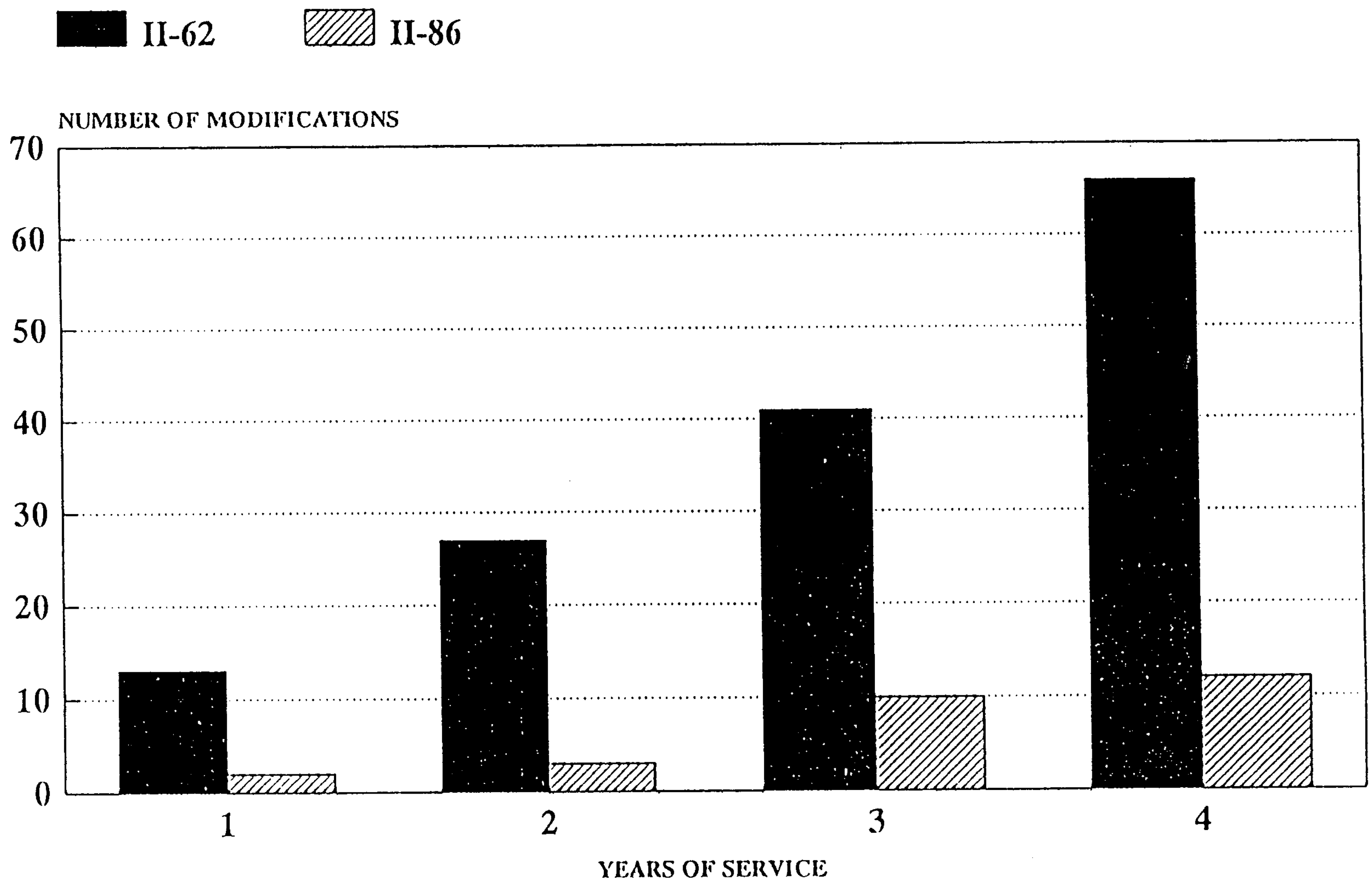

Figure 11 II-62 and II-86 Flight Controls Modifications

Airborne radars have also been an ongoing problem. From the days of vacuum tube technology, airborne radars have seldom exceeded a 100-hour MTBF. A major contributor to that unreliability was and is the transmitter-receiver (TR). With the emergence of economical TR modules in phased array radars, the mission reliability will be greatly improved. When a single module fails, sensitivity will be reduced, but the function will not be lost. This "graceful degradation" feature will do much to improve airborne radar reliability.

Additionally, new display technology will eliminate the use of cathode ray tubes (CRTs) in aircraft. While CRT reliability has been continuously improved over the years, the very high voltages needed have usually posed reliability problems. And CRTs are bulky even without the packaging needed to ensure their survival.

Radar data processors have been the reliability downfall of many systems. The ever increasing computer power available from single chip processors will simplify the design challenge and perhaps some of the performance increase can be dedicated to redundant processing.

New avionic mechanical packaging techniques are evolving to simplify on-aircraft repair and improve avionic structural integrity. Avionic connectors continue to be a vexing problem. With the ever increasing density of pin connections, an electrical answer may not be possible. Perhaps increased use of multiplexed fiber optics will prove to be an answer.

Aircraft engine reliability has increased drastically over the past two decades. Noticeable improvement resulted from electronic fuel controls replacing the electromechanical nightmares of days past. Advances in avionics will mean further improvement in fuel control function reliability. Materials sciences advances have also contributed to rotating machinery durability and more such advances are approaching maturity. Ceramics and metal matrix composites may prove to be a low cost solution to many high temperature problems.

Efforts are ongoing to achieve a more electric aircraft. This effort strives to minimize or reduce the use of airborne hydraulic, pneumatic, mechanical and accessory gearbox systems. These would be replaced by high reliability electrical controllers and high efficiency electrical motors. Weight and space savings are expected to be accompanied by improved reliability and maintainability.

Improving reliability will mean major changes in the way systems are operated and maintained. Many avionic units are reliable enough for two-level maintenance (on aircraft and depot) now. In the future, most shop type maintenance will become redundant and, some equipments will require only single level maintenance - they will be discarded upon failure.

The increased reliability has already made it possible to consider composite U.S. Air Force Wings. For decades, most wings were a single aircraft type to take advantage of the economies of scale in the shop repair environment. This greatly increased the command and control problems when different aircraft types were needed for a mission. Now, it is increasingly feasible to assign multiple aircraft types to the same wing and greatly increase unit cohesion.

And, the maintenance process will also change. Built-in-test is a continuously improving discipline. Artificial intelligence tools like expert systems, fuzzy logic, and neural networks all hold promise to make fault diagnosis better and cheaper.

Microelectronics makes it possible for each individual unit to remember it's own operations (including stress) use, failure/repair history and modification record. Maintenance malpractice will be easier to isolate and correct. Intermittently failing units will be found quicker.

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3. MIL-STD-470, *Maintainability Program Requirements for Systems and Equipment* (Washington, D.C., U.S. Department of Defense. 1966).

4. MIL-STD-1629A, Procedures for Performing Failure Modes, Effects and Criticality Analysis (Washington, D.C., U.S. Department of Defense, 1980).

5. AFR 800-18, *Reliability and Maintainability Program for Systems, Munitions and Equipment* (Washington, D.C., U.S. Air Force, 1983).

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APPENDIX A
RELIABILITY AND MAINTAINABILITY DATA COLLECTION ELEMENTS

This appendix discusses the different elements of data needed from maintenance performed on the equipment being tested. Figure A1 is the standard form used by the U.S. Air Force Systems Command. This form is completed for all work, scheduled and unscheduled, performed on the test aircraft. The form is similar to those used in regular fleet service, but asks for the more detailed data needed in a test environment. Not all of the information on Figure A1 is essential to an R&M test program. Where such entries are unique to the U.S. Air Force, they are not discussed in this appendix. Figure A2 is a redrawn and translated version of the form used by the U.S.S.R. for data collection during fleet service. The similarities are interesting to note.

CONTROL NUMBER (Block A on Figure A1) - The control number is a means of linking all related maintenance actions into a single event. All actions caused by a single failure or flight discrepancy have a single control number. With this number, all related actions, on the aircraft or at a shop, depot or vendor can be related. For much of the U.S. military, this nine digit is called a job control number. The first two digits (e.g. 92) are the decade and year. The next three digits (e.g. 185) are the Julian date that the problem was discovered. The final four digits are assigned sequentially beginning with 0001 for the first job of the day. Once originated, this number is assigned to all subsequent related work, regardless of when the work is done. When prefixed with a unique base or location code, the job control number uniquely identifies a single job within the U.S. military.

VEHICLE TYPE (Block 4 on Figure A1) - The type of aircraft or munition (e.g. F-15E, GBU-15) being maintained. Called the Model-Design-Series by the U.S. Military, this element simply names the vehicle.

SERIAL NUMBER (Block 5 on Figure A1) - The serial number of the item being maintained. For aircraft, the tail number is often used.

WORK CENTER (Block 3 on Figure A1) - The organization responsible for the maintenance being recorded. Shows whether the work was on-aircraft, shop or depot. Can also be used to show which vendor is repairing equipment.

TIME/CYCLES/MILES (Block 6 on Figure A1) - The measure of equipment usage or accumulated stress. Flight hours for aircraft for example. Normally rounded to the nearest whole number.

WHEN DISCOVERED DATE/TIME (Block 7 on Figure A1) - The date and time that the failure was discovered. Not used for scheduled maintenance or servicing type actions. Used as a cross check on the Julian date component of the control number and to calculate times between failures.

REPORT DATE (Block 8 on Figure A1) - Date the maintenance recorded was actually done (as opposed to the date failure occurred). Used to calculate maintenance expenditures per calendar period and elapsed time out of service statistics.

EQUIPMENT CLASS (Block 9 on Figure A1 - part of work order number) - A code showing if item being repaired is aircraft, munition, support equipment, etc.

TYPE MAINTENANCE (Block 9 on Figure A1 - part of work order number) - A code showing if maintenance was servicing, inspection, repair, etc.). Used to calculate statistics for different types of maintenance.

WHEN DISCOVERED CODE (Block 11 on Figure A1) - A code showing when the failure was found (not used for scheduled maintenance) such as preflight, in-flight, etc.) Used to classify severity of failure.

ENGINE POSITION NUMBER (Block 12 on Figure A1) - A number showing which individual is being maintained when the equipment has more than one like item installed. Used to identify failure trends as a function of equipment location.

ACTIVITY IDENTIFICATION (Block 13 on Figure A1) - A code showing the geographic location where maintenance is being performed. When combined with the control number, a military wide unique number is formed.

MANUFACTURER (Block 14 on Figure A1) - The manufacturer of the equipment being repaired. Used

Line	A. JOB CONTROL NUMBER	B. PRI	C. TIME SPEC REQD	D. WORK AREA	E. ESTIMATED MANHOURS	F.	1. COPY NO	2. REPORT NUMBER
10	0079401						1	001532

	3. BASIC WORK CENTER	4. ITEM IDENTIFICATION	5. SERIAL NUMBER	6. TIME/CYCLES MILES	7. WHEN DISCOVERED TIME (Day-Mo-Yr-Hours)
10	mmshp	PROD TGT POD	1002	0096	070190730

	8. DATE THIS REPORT (Day-Mo-Yr)	9. WORK ORDER NUMBER	10. ORIG. REPORT NUMBER	11. WHEN DISC CODE	12. ENG POSN NO.	13. ACTIVITY IDENT
10	07019	PB0002PT		F		LN

FAILED ITEM

	14. MANUFACTURER	15. NOUN - ENGINE TYPE/MODEL/SERIES MOD	16. SERIAL NUMBER	17. TIME/CYCLES/MILES	18. PART NUMBER
20	00Q93	Low Voltage P/S	5600001		717538-1

	19. WORK UNIT CODE	20. SYMBOL	21. HOW MAL	22. FEDERAL SUPPLY CLASS	23.	24.
20	74ND0		842	5960		

INSTALLED ITEM

	25. MANUFACTURER	26. NOUN- ENGINE TYPE/MODEL/SERIES MOD	27. SERIAL NUMBER	28. TIME/CYCLES/MILES	29. PART NUMBER
30	00Q93	Low Voltage P/S	56000028		717538-11

40 THRU 49

G. SUPPLY DOCUMENT NUMBER (Issue or Demand)

30. DESCRIPTION OF DISCREPANCY OR MAINTENANCE REQUIRED

Power Supply has no output.

H. DISCOVERED BY

SSgt Howell

Line	31. PRE FIX	AFSC	SUF	NR	32. START	33. STOP	34. DELAY CODE	35. START	36. STOP	37. DELAY CODE	38. WORK UNIT CODE	39. ASSISTING WORK CENTER	40. UNITS	41. ACT
50		455X0	M	1	0750	0800							01	R
51														
52														
53														
54														
55														
56														
57														
58														
59														

	42. TO NUMBER	43. TO DATE (Day-Mo-Yr)	44. TO PROCEDURE	45. TOOLS/AGE	I. CORRECTED BY
60					

61 THRU 69

46. CORRECTIVE ACTION

Power SUpply removed and replaced with later version. Pod operates satisfactorily.

J. INSPECTED BY

K. SUPERVISOR	L. RECORDS ACTIONS	M. DATE TRANSCRIBED (Day-Mo-Yr)	N. TRANSCRIBED BY
	☐ UNCLEAR DISCREPANCY ☐ REPLACEMENT TIME CHANGE ☐ DATA TRANSCRIBED TO RECORDS	Figure A1	AFSC Form 258

AFSC FORM FEB 81 ,258–4 PREVIOUS EDITION WILL BE USED. **MAINTENANCE DISCREPANCY/PRODUCTION CREDIT RECORD**

Figure A1 AFSC FORM 258

I. Date of detection *17.08.1973.*

II.	Aircraft		Engine		Assembly, station instrument	
Conditional designation (type, modification) *21*	*Il-18*				*PПОН-2*	
Manufacturer						
Complete factory serial number	*184007504*				*082*	
Flight time operating time — from the beginning of operation	*18833* hours	*11827* landings	hours		hours months	*11341*
1 — after the last repair	*6803* hours	*3784* landings	hours		cycles landings	*3508*
Date of issue (installation on given vehicle) (month, year)	of issue		of issue	installation	*03.84* issue	*08.73* installation
Quanity of repairs (date of the last repair) (month, year)	quantity of repairs	date of last repair	quantity of repairs	date of last repair	quantity of repairs *1*	date of last repair *05.71*
AP3/APM [Aircraft Repair Plant/Aircraft Repair Shop]					*402*	

III. Record numbers in accordance with the designations of category III of reverse side of card

A. It occurred	*1*	B. Reason	*7*	C. Detected	*1*	Time of removal on aircraft	*0 h. 30 min.* h. min.
D. Consequences	*8*	E. Method of elimination on vehicle	*2*	F. Buletin No.	*2*	Labor expense of removal	*05* man-hours

IV. System *PПОН-2*

Address of malfunction

Assembly, instrument	*Unit No. 2M*
Unit, subassembly	*БГ*
Part, type of element (module)	*П51-1 (K-27)*
Scheme number *П51-1* designation by specification	Unit: — — *2*; Subpanel: — — *1*; sub-assembly: — —; stage: —; elements (write appropriate digit): *02*; scheme No. of element of module: — — *1*

(not used)

Description of malfunction

external manifestation (which is noticed)	*Sectoring, there is no coverage of the 'ARCh'.*
character, essence (which occured) (in the case of REЭO write the appropriate digit from reverse side)	*09*
reason (why malfunction occured)	
emergence condition (which contributed)	*Normal operation*

(not used)

VI. Supplementary information *312 0.2 0.1 30 0001 33*

Signature *Ivanov* Signature *Malakhov* Signature *Petrov*

Figure A2 U.S.S.R. Aircraft Maintenance Record

to identify problems unique to different equipment makers.

NOUN (Block 15 on Figure A1) - The name of the part being removed or repaired. The name is taken from a manual with standard names.

SERIAL NUMBER (Block 16 on Figure A1) - The serial number of the unit being repaired or replaced. This number is essential to finding "bad actor" units.

TIME/CYCLES/MILES (Block 17 on Figure A1) - The measure of stress on the unit being repaired or replaced. This accumulated stress measure is taken from self-contained elapsed time counters.

PART NUMBER (Block 18 on Figure A1) - A number assigned by the manufacturer. This number is the only way to tell the version of a part. During development programs, parts are often improved many times and the part number changes with each equipment change. For example, the initial version might be numbered 191238. Then, the first change would be 191238-1. Other number schemes are used, but mostly, the higher the "dash number" the later the version. The number of the part being repaired is essential for analyzing failure modes.

WORK UNIT CODE (Block 19 on Figure A1) - The Work Unit Code is a "hardware address" used by the U.S. Navy and Air Force to hierarchically define the the equipment. For example, the radio navigation system might be coded as 71000. The system could contain several functional capabilities such as TACAN and ILS. Then, the TACAN would be coded 71A00 and the ILS 71B00. Continuing the example, the TACAN receiver/transmitter line replaceable unit(LRU) would be coded 71AA0, the TACAN control panel 71AB0 and the antenna 71AC0. Finishing the example, the modules within the receiver/transmitter (shop replaceable units - SRUs) would be coded 71AAA, 71AAB and so forth.

This identification scheme is necessary because part numbers change too frequently and are to complex to be useful. U.S. Military Specification 38769C, A Manual, Technical, Work Unit Code contains more details.

SYMPTOM/MALFUNCTION CODE (Block 20 on Figure A1) - The code is a numeric code to indicate the symptom of the equipment initially and, when the failure is understood, to indicate the failure mode among a class of possible modes. This code is used for computer processing.

Several classes of codes are used. The first class consists of codes that describe inherent failures. Inherent failures are those failures caused by an inherent defect in the failed part.

The second class lists induced failure modes. That is, those failures where the defect was not inherent in the the failed part. Examples include secondary failures, maintenance error and weather damage.

A third class includes the "no-defect" failure. This occurs when a observed performance anomaly cannot be traced to a broken part and the symptom disappears.

A final list of codes is termed "product improvement". These codes are used when the maintenance work is not being done to repair a failure, but rather to improve the equipment. Modifications are the common example.

BUILT-IN-TEST CODE (Block 24 on Figure A1) - This code shows the use and accuracy of the aircraft built-in-test for the maintenance being recorded. The code contains two characters to show how faults where identified and isolated. Codes used on the C-17 test program are:

1. BIT detected a malfunction when one existed.

2. BIT failed to detect a malfunction when one existed.

3. BIT correctly isolated to the failed line replaceable unit (LRU).

4. BIT did not isolate to the failed LRU.

   a BIT assisted but technical data and support equipment where needed.

   b. Technical data and/or support equipment where only method.

   c. Procedures did not work.

5. BIT indicated a malfunction where none existed. (False Alarm)

INSTALLED ITEM INFORMATION (Blocks 25 to 29 on Figure A1) - Installed item information is needed when an LRU is changed. The data needed are identical in nature to that necessary for the equipment being removed or repaired.

DESCRIPTION OF DISCREPANCY (Block 30 on Figure A1) - The fault description is one of the more critical data elements. Other codes and elements can be corrected if the narrative is accurate and complete. For inflight discovered faults, the aircrew must be carefully questioned to get all of the details recorded. The details are important to ease the maintenance task of finding the problem and important to the reliability engineer to understand the problem and the impact.

SPECIALTY CODE (Block titled AFSC on Figure A1) - This code describes the specialty of the maintenance technician performing the work. Engine repair, avionics technician and sheet metal specialist are examples of the different types of maintenance personnel. This information is used to calculate the number of the different types of maintenance specialists needed for a mature aircraft.

START/STOP TIMES (Blocks 32/33 and 35/36 on Figure A1) - These are the clock times when maintenance work was initiated and terminated. These times, together with the maintenance crew size, yield the man-hours needed for a specific repair task.

CREW SIZE (Block titled NR on Figure A1) - The number of maintenance personnel working.

DELAY CODE (Blocks 34 and 35 on Figure A1) - Although not an essential data element, the reason for maintenance delays can be helpful in analyzing maintenance tasks.

UNITS (Block 40 on Figure A1) - A code to show whether the work is complete after this action is finished. This is necessary because some repair tasks continue over several days and more rarely, several weeks.

ACTION TAKEN CODE (Block 41 on Figure A1) - This entry is a code showing the type of repair accomplished. Typical codes represent actions such as remove and replace,clean, and troubleshoot. A typical maintenance action will consist of several of these. For example, the first action might be troubleshooting. When the fault is isolated, a remove and replace action would follow. Finally, a system test would verify the effectiveness of the repair.

CORRECTIVE ACTION (Block 46 on Figure A1) - This is a most important data element for the R&M engineer. A complete and accurate description of the maintenance performed is essential to understand the work needed to correct the fault. This description should vary in type as the work is done at different echelons of repair, For example, the on aircraft work should describe the method of fault isolation and the action needed to eliminate the fault. The retest done to verify the repair should also discuss any abnormalities encountered.

When a LRU is repaired, the shop performing the work should describe any tests performed, shop replaceable units (SRUs) replaced, the repair verification effort and anomalies encountered.

When a shop replaceable unit is repaired, the repair effort must include considerable detail as to the cause of the failure in addition to the repair actions taken. Many times, the technicians can add invaluable detail which will help understand the root cause of the failure. For example, technicians should note any physical damage present before attempting repair. In some cases, the R&M engineer should participate in this inspection. Documentation such as photographs can be helpful. Some damage symptoms such as overheat damage are vital to determining the cause and such evidence must be preserved. Highly skilled technicians are needed to perform theses autopsies without inducing additional damage or destroying evidence. Failed parts with no external damage symptoms must be carefully preserved in order that a detailed physics of failure analysis can be performed in the proper laboratory environment.

All resulting information should be entered as corrective action. Further, when a change or fix is developed to prevent failure recurrence, the details and implementation should also be noted.

APPENDIX B
JOINT RELIABILITY AND MAINTAINABILITY EVALUATION TEAM (JRMET) CHARTER

1.0 Purpose - To collect and evaluate R&M data in accordance with the Test and Evaluation Master Plan.

2.0 Scope - The JRMET will establish and implement procedures for the collection and evaluation of R&M data from flight test operations or other mutually agreeable sources as appropriate. The JRMET will also identify and document R&M problems along with corresponding corrective action.

3.0 Organization - The JRMET will consist of designated representatives from Program Office, Test Organization, Material Command, Using Command and the Contractors. Representation from subcontractors and Government Furnished Equipment suppliers will be on an as required basis. The Program Office representative will serve as chairman and have final authority should conflict exist on contractual issues. The JRMET will be supported by government and contractor personnel to observe operations; keep records; and collect, edit, and analyze data.

4.O JRMET Responsibilities:

a. Determine R&M data collection requirements during the flight test program.

b. Ensure incorporation of the data collection requirements into test plans/procedures.

c. Determine the source and extent of ancillary data to be used to supplement data gathered during the flight test effort.

d. Ensure the implementation of a responsive R&M data collecting, processing and analyzing system.

e. Ensure the availability of data products needed for assessment.

f. Identify R&M problem areas.

g. Ensure exchange of data among appropriate organizations.

h. Validate, assess and classify R&M data collected, in accordance with approved test plans.

i. Rule on other issues, as necessary, that are not covered by applicable specifications/agreements.

j. Discuss and assess the impact of R&M problem areas on support equipment, training, technical manuals, maintenance,and operational procedures.

k. Document corrective action, either planned or implemented, to correct any R&M difficulties.

1. Establish methodology for accounting for configuration differences among test aircraft and procedures for relating such differences to the intended configuration.

m. Ensure classification and tracking of mission essential subsystem critical failures.

n. Ensure that a methodology for factoring ground operating hours vs. flying hours is established.

4.1 JRMET/Program Office Management - The Program Office R&M engineer will be responsible for:

a. Coordination for JRMET activities

b. Convening and chairing JRMET meetings.

c. Preparation of JRMET minutes and assignment of action items.

d. Serving as a focal point for communications with the contractors.

e. Serve as a focal point for reports/data requests and distribution.

4.2 JRMET/Test Organization Support - The test director will have overall responsibility for the Test Organization effort during the evaluation. The test

organization representative on the JRMET will be responsible for the R&M coordination at test site. A JRMET support team will be established assist the test organization representative in his responsibilities, which will include:

a. Maintaining surveillance over maintenance and inspections.

b. Providing failure analysis on selected nonrepairables for which the contractor is not responsible.

c. Obtaining failure documentation from government or contractor personnel.

d. Obtaining follow-up detailed failure analysis from contractors' and maintenance depots.

e. Obtaining debriefing data from each test flight.

f. Insuring that the team's technical documents are kept current.

g. Calculating R&M statistics and performing other analyses required by the JRMET.

h. Processing mission, failure and maintenance data

i. Preparing and submitting status documentation.

j. Preparing R&M reports.

4.3 JRMET/Contractor Support - The contractors will have access to and/or be provided with the R&M data collected during the evaluation. These data will be made available through a test control, records, and data center established and operated by the test organization. The contractor will be responsible for:

a. Supporting JRMET activities.

b. Providing R&M data for all contractor performed maintenance occurring at the test site; and for those maintenance actions at the contractors facilities to the extent necessary to support the program.

c. Providing ancillary R&M data as required by the JRMET. These data will include historical data for existing equipment as well as prediction/estimates for new or modified hardware.

d. Providing detailed analysis of failures occurring in the flight test program as appropriate.

e. Supporting R&M analyses and data evaluation.

5.0 Authority - The authority for establishing the JRMET activity is contained in AFR 800- 18, dated 15 Jun 82 (The governing R&M directive for the U.S. Air Force).

Annex

AGARD Flight Test Instrumentation and Flight Test Techniques Series

1. Volumes in the AGARD Flight Test Instrumentation Series, AGARDograph 160

Volume Number	Title	Publication Date
1.	Basic Principles of Flight Test Instrumentation Engineering (Issue 2) Issue 1: edited by A. Pool and D. Bosman Issue 2: edited by R. Borek and A. Pool	 1974 1994
2.	In-Flight Temperature Measurements by F. Trenkle and M. Reinhardt	1973
3.	The Measurements of Fuel Flow by J.T. France	1972
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5.	Magnetic Recording of Flight Test Data by G.E. Bennett	1974
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2. Volumes in the AGARD Flight Test Techniques Series

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	Part 2: Nonlinear Analysis and Manoeuvre Design by J.A. Mulder, J.K. Sridhar and J.H. Breeman	1994
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14. Abstract

This AGARDograph outlines the rudiments of reliability and maintainability (R&M) evaluations conducted during initial flight test programs. Many organizations, both military and civilian, prefer to defer R&M evaluations until the new equipment has been delivered to the eventual user. The U.S. Air Force Flight Test Center has long conducted R&M evaluations during initial flight test and has found value in that process. This document discusses, first, the objectives of the early evaluations. Then, the acquisition process and the test planning process, as they relate to R&M evaluations, are presented. The test planning section discusses the data needed for a successful R&M evaluation and the sources of such data. The conduct of the test, analysis of results, and subsequent reporting methods are delineated. Follow-up actions that are needed after the test are considered. In conclusion, the document lists some R&M considerations for the future.

This AGARDograph, originally sponsored by the Flight Mechanics Panel of AGARD, has been published on behalf of the Flight Vehicle Integration Panel.